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MAGNETIC TAPE RECORDING

-

S. A. Sherwin, Jr.

MAGNETIC TAPE RECORDING

by

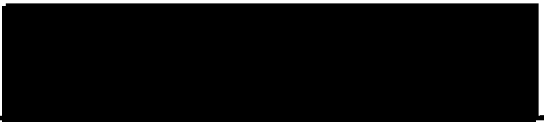
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Submitted in partial fulfillment
of the requirements
for the degree of
MASTER OF SCIENCE

United States Naval Postgraduate School
Annapolis, Maryland
1948

This work is accepted as fulfilling
the thesis requirements for the degree of
Master of Science in Electronics Engineering

from the
United States Naval Postgraduate School


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7552

PREFACE

All practical work and a large part of the research preparatory to writing this thesis were done between January 5 and March 19, 1948, at the laboratories of the Advanced Development Group, R.C.A. Victor Division, Camden, New Jersey. The author desires to express thanks to officials of RCA Victor Division and more particularly to Mr. M. C. Batsel, Mr. H. Belar, Dr. E. W. Kellogg, and Mr. G. L. Dimmick, for making it possible for him to work with this group. He also desires to express his sincere appreciation to Mr. Earl Masterson, Mr. D. R. Andrews, Mr. H. E. Roys, and Mr. Virgil Grantham, whose technical advice and assistance were invaluable.

TABLE OF CONTENTS

Chapter	Title	Page
	Certificate of Approval	i
	Preface	ii
	Table of Contents	iii
	List of Illustrations	iv
	Table of Symbols	vi
	List of Definitions	viii
I	Historical	1
II	The Problem	5
	1. General	5
	2. Erasing	6
	3. Biasing and Recording	9
	4. Reproducing	13
III	Frequency Response	15
	1. General	15
	2. Recording	15
	3. Reproduction	18
IV	Noise	34
	1. Mechanical	34
	2. Magnetic	34
	3. System	35
V	Field Measurements	37
	1. General	37
VI	Tapes	40
	1. Description	40
	2. Manufacture	41
	3. Testing	41
VII	Driving Systems	45
	1. General	45
VIII	Construction of Heads	47
IX	Conclusion	50
	Bibliography	51

LIST OF ILLUSTRATIONS

Figure No.	Title	Page
1	Block Diagram of a Typical Tape Recording System	52
2	Curves to Explain Erasing Action	53, 54
3	Curves to Explain Biasing Action	55
4	Curves to Explain Biasing Action	56
5	Relative Magnetizing Force as a Function of Distance Along the Path of the Recording Medium for an Experimental Recording Head	57
6	Frequency Response Curves Obtained Using an Experimental Recording Head	58
7	Frequency Response Curve Obtained Using a .040" Gap with Brass Spacer in the Playback Head	59
8	Frequency Response Curve Obtained Using a .022" Gap with Brass Spacer in the Playback Head	60
9	Electrical Set-Up for Taking Field Measurements with Magnetic Heads	61
10	Field Distribution Curves Taken With the Set-Up of Figure 9	62
12	Frequency Response Curves of Scotch, Hyflux, and Brush Tapes	64
13	Frequency Response Curve of DuPont MT-78 Tape at 18"/sec.	65
14	Frequency Response Curves of Scotch Tape at Various Speeds	66
15	Frequency Response Curves of Tape (System Uncompensated), Recording Compensator Alone, and Playback Compensator Alone, Showing Circuits	67
16	Composite Curves Obtained by Adding Curves of Figure 15	68

LIST OF ILLUSTRATIONS
(CONTINUED)

Figure No.	Title	Page
17	Actual Overall Frequency Response of System With Components of Figure 15	69
18	Curves Showing Construction of Frequency Response at One Speed From Known Response at Another Speed	70
19	Construction of a Ring Type Head	71
20	Mechanical Set-Up for Making Field Measurements	72
21	Input-Output Curve for German Type C Tape	73
22	Input-Output Curves For Various Tapes	74
23	Input-Output Curves for German Type IG Tape	75
24	Input-Output Curves for Minnesota Mining Tape (Paper Base)	76
25	Total Harmonic Distortion Vs. Reproducing Level for Various Tapes	77
26	Total Harmonic Distortion Vs. Reproducing Level for Five Values of H. F. Bias	78
27	Output Level and Total Harmonic Distortion as Functions of Bias Voltage for German Type IG Tape	79
28	Output Level and Total Harmonic Distortion as Functions of Bias Current for a Typical American Tape	80
29	Simplified Diagram of Masterson Tape Driving System	81
30	Diagram Showing Construction of Pole Piece for Ring Type Head	82

LIST OF SYMBOLS

In equation (1), page 19,

E is the root mean square voltage at the terminals of the coil.

B_m is the maximum value of the remanence corresponding to the maximum instantaneous audio signal.

S_t is the tape speed.

λ is the wavelength corresponding to the audio signal recorded on the medium.

l_g is the air gap width in the playback head.

K is a constant whose value depends on the units and upon the coupling between the recording material and the magnetic circuit of the playback head as well as on the size and configuration of the magnetic circuit and the properties of the reproducing coil itself.

In equations (2) through (15), pages 21 to 24,

$f(x)$ is the magnetizing force at the distance x from the center of the gap.

A is the magnetizing force at the central peak.

B is the magnetizing force at the lateral peaks.

a is the abscissa to the point where $e^{-\alpha_1 x}$ becomes negligible.

b is the abscissa to the point where $e^{-\alpha_2 (-x+c)}$ becomes negligible.

c is the abscissa to the point where $e^{-\alpha_3 (x-c)}$ becomes negligible.

m is the instantaneous magnetizing force in ampere turns per inch.

LIST OF SYMBOLS
(CONTINUED)

M is the maximum magnetizing force in ampere turns per inch.

λ is a wavelength in inches.

V is the velocity of the tape in inches per second.

x is the distance from the center line of the gap in inches.

t is the time in seconds.

f is the frequency in cycles per second.

N is the number of turns in the coil.

LIST OF DEFINITIONS

Coercive Force	The demagnetizing force necessary to bring the induction in a magnetic material to zero along the normal hysteresis loop.
Remanence	The magnetic induction which remains in a magnetic circuit after the removal of an applied magnetomotive force.
Residual Induction	The magnetic induction at which the magnetizing force is zero when the material is in a symmetrically cyclicly magnetized condition.
Retentivity	The residual induction.
Saturation	When all of the elementary magnetic particles become oriented in one direction, a material is said to be saturated.

CHAPTER I

HISTORICAL

The theory of magnetic recording is not new. In 1898, Valdemar Poulsen took out a patent on a device which he called the "telegraphophone". This device he used in conjunction with his arc-system of radiotelegraphy. Telegraph messages sent at high speed were magnetically recorded on a steel wire and then played back at a slower speed so that they could be transcribed easily by the receiving operator. This process did not require high-fidelity reproduction, and effects of frequency distortion and variations of speed of the recording medium were not important. The process of recording as used by Poulsen was impractical for recording and reproducing speech, much less music; however, it was the first introduction of a principle whose importance in the field of recording is only now becoming fully realized.

During the latter part of the 1910-1920 decade, a wire recorder was sold by the American Telegraphophone Company. It was thought that the system could be used for dictating and other business purposes. The speech quality was adequate but commercially the machine was not competitive with the simpler wax machines. It used .010" music wire at a linear speed of about five feet per second.

In 1924 Dr. Stille, a German scientist, studied the magnetic recording method. He is credited with improvements in the magnetic and mechanical systems; advantages obtained chiefly due to the use of steel tape instead of wire.

The British first worked seriously with magnetic systems in 1930, when the British Broadcasting Corporation tested an instrument called the "blattnerphone". The quality of reproduction of this instrument was far from satisfactory, and considerable experimental work was carried out in Great Britain, mainly under the auspices of B. B. C. and the Marconi Wireless Telegraph Company. The British very early recognized the potential value of this principle for broadcast transcription purposes; the first important transcribed program to be sent out to the Empire was on Christmas day, 1932, and included a speech by the late King George V.

The medium used in the past for magnetic recording has never been entirely satisfactory. A continuous effort to improve it is being made. There are three media currently used to record signals magnetically. These are steel wire, steel tape, and non-magnetic tape with a coating of magnetic particles. Wire was used by Poulsen in his original machine; great improvements have been made in the past few years, and wire recorders of fairly good quality now are quite common.

Steel tape, introduced by Stille, gave several advantages over wire. Distortion due to twisting of the medium was eliminated; snarling difficulties encountered when using wire were avoided by winding the tape on pancake-shaped reels, and higher frequency response was obtained with lower tape speeds. The British Broadcasting Corporation has used magnetic recorders with steel tape.

Several methods of impressing the signal on the recording medium are available. In "longitudinal" recording, two pole pieces are placed on opposite sides of the medium and displaced from each other along

the path of the medium. This method was used originally for wire recording. It was necessary to make the longitudinal separation of the poles rather large in order to minimize the distortion due to twisting of the wire, and this in turn made it necessary to use a high wire speed in order to obtain satisfactory response at high frequencies. This high speed caused rapid wear on the pole pieces, making it difficult to construct and hold them so that they would ride smoothly against the wire. These variations in contact with the wire changed the magnetic reluctance of the flux path so that the signal strength varied and an excessive amount of noise was introduced.

In "transverse" recording, using tape as the recording medium, the pole pieces are placed perpendicular to an edge of the tape and parallel to the surface. This system has not been much used.

The third method used is called "perpendicular" recording. The two pole pieces are mounted opposite each other on opposite sides of the tape as in longitudinal recording, but without horizontal displacement.

In 1932 Schuller of Germany developed the ring type head which gave much higher fidelity than had been obtained with other heads and which is in general use. The ring head uses substantially longitudinal magnetization; the principal difference being that both pole pieces are on the same side of the tape. The separation of pole pieces is very small, being of the order of mils, or thousandths of an inch. This type of head will be described in detail later.

Schuller used the ring head in conjunction with a recording medium consisting of a non-magnetic carrier film with a thin coating of ferromagnetic powder. The advantages of this medium over the steel tapes

that had been used up to that time were that it was much lighter and thinner, gave higher fidelity, and was much cheaper to manufacture. It had the disadvantage of much less sensitivity than steel tape. Another disadvantage of any system using the ring type head is that the entire magnetic flux cannot be used but only the stray flux from the gap. Both these difficulties cannot be overcome by sufficient amplification, and this system, with variations, is the one in most general use today.

CHAPTER II

THE PROBLEM

1. General.

A typical system for recording of sound on magnetic tape is shown in figure 1. Three electromagnets are arranged in a line, with provision for driving a recording medium over them in succession at a uniform speed, from a "hold-back" reel to a "take-up" reel. The first electromagnet is called the "erasing head", the second the "recording head". These two are active only while recording. The third electromagnet is active only during reproduction and is called the "playback head".

The high frequency oscillator as shown feeds a signal to the erasing amplifier, which provides a high frequency current to the coils of the erasing head. The oscillator also drives the bias amplifier, whose output goes to the coils of the recording head. Sound from the audio signal source goes to the recording amplifier, and from there to a recording filter, which serves to improve the frequency response at the lower end of the audio spectrum. The output from the filter is mixed with the output from the bias oscillator and fed to the coils of the recording head.

The recording process is as follows: The tape is passed over the erasing head, which emits a strong magnetic field changing sinusoidally at high frequency (usually from 30 to 100 kilocycles). This field erases any signals which may have been previously recorded. The tape then passes over the recording head, where it is subjected to two superimposed magnetic fields, varying at different frequencies. The

high-frequency bias field serves to improve the linearity of the recording; the field set up by the audio signal induces a similar field in the magnetic particles of the tape, a portion of which field remains in the tape after it has left the recording head. During reproduction, the tape passes over the playback head. The remanent field left on the tape by the recording head induces a similar field in the poles of the playback head, and this changing field induces a voltage in the playback coils. This voltage drives a preamplifier, whose output goes to a playback filter, which improves the frequency response at the upper end of the audio range. The output of the playback filter goes to the playback amplifier and the resulting output drives a speaker.

2. Erasing.

At present the best method of erasing the tape appears to be the use of a high-frequency magnetic field applied to the tape over the comparatively long time period that the magnetic element remains opposite the gap of the erasing head. This field must be strong enough to saturate the magnetic material in both directions, and its erasing ability depends on self-demagnetization and on the fact that a magnetic element leaves the erasing gap gradually rather than instantaneously.

The erasing field encountered by the magnetic element as it enters, passes through, and leaves the gap is a sine wave whose amplitude is greatest near the center of the gap and decreases towards the edges. (see Figure 2(a).) It should be noted that the field does not disappear abruptly at the edges of the gap, but extends slightly beyond both edges. This fact is of no particular significance on the entrance side, but has the greatest significance on the exit side.

The action of the high-frequency field in erasing can be explained as follows:

Assuming a tape speed of ten inches per second, an erasing gap of 10 mils and an erasing frequency of 10 kilocycles, a small magnetic element will remain in the gap during ten cycles of erasing field. Referring to figure 2(a), the particle enters the effective gap at point 1, with a positive remanent magnetism from previous recording. In the progress of the particle through the gap it will be acted on by successive positive and negative magnetic fields, and the resultant states of induced magnetism will be 1, 2, 3, 4, etc., up to 14 (figure 2(b)) corresponding to the same numbered points on figure 2(a). Note that the hysteresis curve approaches more and more closely the saturation loop as the inducing field swings farther and farther either side of zero, until at about point 9 saturation is reached, and for the next few cycles the saturation loop is followed.

As the center of the gap is passed, the swing of the field begins to decrease, and the hysteresis curve follows the path shown in figure 2(c). The saturation loop is followed for another few cycles until point 14 is reached, after which the curve begins to trace a loop of steadily decreasing area which gradually approaches the origin as a center. The more gradual the decline of the amplitude of the sine wave, the more closely the loop approaches the origin and the more completely the particle is demagnetized when it leaves the gap. The fringing effect at the trailing edge of the gap serves to subject the particle to a small additional number of complete cycles of erasing field of small amplitude, which serve to bring the hysteresis

esis curve closer to the origin. Actually, some residual magnetism appears inevitable, but this is reduced somewhat by the self-demagnetization always present at high frequencies, and the resultant noise is reduced proportionally.

Since the magnetic element must remain in the erasing gap during several cycles of the erasing field, it follows that the gap of the erasing head must necessarily be rather wide. It will be seen in the discussion of magnetic heads that this is true.

There are various methods used for producing the high-frequency erasing field, two of which will be described. Each involves a Hartley oscillator. In the first method, a 6L6 tube is used as the oscillator and the output of the erasing head is taken directly from the tank coil, the amount of erasing current being determined by a variable coupling capacitor. This method has the advantage of simplicity, but varying the erasing current results in a change in the oscillator frequency. This appears to be unimportant (within limits) for normal operation, but renders the arrangement unsatisfactory for some test purposes, for example, for tests on tape with a given erase current at varying frequencies or at a given erase frequency with varying currents.

For test purposes the other method is more satisfactory: a 6J7 tube used as a Hartley oscillator drives a 6L6 as a final amplifier; the 6L6 load is a parallel circuit consisting of the erasing head and a capacitor to tune it to the oscillator frequency. This capacitor serves the dual purpose of cleaning up the wave form and of building up the voltage across the erasing head, which was found to be necessary to obtain the high current required for erasing

some tapes of high coercivity. A ganged switch is supplied to change both this capacitor and the tank tuning capacitor simultaneously for changing frequency for test purposes, and the frequency is variable in steps of about 10 kilocycles from 20 kilocycles to 100 kilocycles.

3. Biasing and Recording.

After leaving the erasing head in a theoretically magnetically neutral condition, the tape passes over the recording head. In the following analysis, we will consider each elementary magnet of the tape as it passes over the recording gap.

In the absence of any biasing field, the curve of remanence vs. magnetizing force is as shown in figure 3. Since this remanence is the inducing field for reproduction, it is obvious that considerable distortion will be introduced unless something is done to improve the linearity of this curve.

A direct current biasing field may be superimposed on the recording signal field, and this has been done, in conjunction with a direct current erasing field. The action is as follows: A strong direct current field is supplied by the erasing head, saturating the recording element, over-riding all components of old signal. When the element leaves the erasing gap it carries a residual field. The direct current biasing field is in the opposite direction, and serves to reduce the net magnetization to zero with no applied signal. When a signal is applied, the field on the recording medium in the gap is badly distorted, but on leaving the gap the hysteresis results in much less distortion, due to remanent magnetism. This distortion can be still further reduced by regulation of the biasing field so as to operate on the proper part of the curvature of the characteristic.

This, however, has two disadvantages: First, though it reduces distortion at one recording level it increases it at another, and second, it leaves a permanent one-way field on the recording material. This field, since it varies slightly from element to element, gives rise to noise in the playback system, the most objectionable feature of this method.

A more satisfactory method and one now used almost universally is to erase the tape with a supersonic field, leaving it magnetically neutral as described earlier, and use a second supersonic field for biasing purposes. The mechanism of the supersonic field in erasing is as follows: Assume that the gap length, tape speed, and biasing frequency have such a relationship that a magnetic element will require 1.5 cycles of biasing frequency to traverse the gap. This would be true in the case of a gap width of 1.0 mils, a tape speed of 10 inches per second, and a bias frequency of 15 kilocycles. This frequency would be too low for practical purposes but will serve for purposes of illustration. As each element passes through the gap it will be subjected at least once to a field corresponding to the instantaneous audio signal plus the peak value of bias field in the same direction. The resultant maximum instantaneous field is the one which in large measure determines the value of the remanent flux density.

In figure 4 three possible cases are illustrated for successive magnetic elements entering the recording gap during a positive half-cycle of audio signal. Referring to the first hysteresis curve, figure 4(b), assume that the element enters the gap in a demagnetized state at time t_1 , at which time the bias field and audio field are

both zero. As the field rises to its first maximum (point P in figure 4(a)) the flux density in the element follows the initial magnetization curve to P'. As the resultant magnetic field in the gap goes through successive values P, Q, R, S, the flux density in the recording particle follows the path P', Q', R', S'. At this point the element is assumed to leave the recording gap, and the remanent flux density is left at X. Graphs, figure 4(c) and (d) represent similar successive flux density changes for elements entering the gap at times t_2 and t_3 . The recording will be linear only if the values of remanent flux density are in direct proportion to the corresponding instantaneous values of audio signal.

An extension of this step-by-step analysis to explain the averaging effect or a complete audio cycle is shown in figure 3. As shown in figure 1, the supersonic bias signal is mixed with the audio signal and the resultant current in the recording coil and field in the gap should be a simple mixed signal without modulation. When no audio signal is present, the record on the tape will consist of a signal at supersonic frequency and low amplitude. The amplitude will be low for two reasons. In the first place, the magnitude of the bias field is adjusted to a value which will just bring the operating point for zero audio signal up to the lower knee of the residual magnetization curve. The corresponding value of residual flux density for most ferromagnetic materials is low. In the second place, self-demagnetization is very pronounced at the supersonic frequency which is used for the bias field because the frequency corresponds to short magnet lengths on the recording medium. Thus the effective remanence is still lower than indicated by the curve under the condition of zero

audio signal.

Now assume a sinusoidal audio signal to be superimposed on the supersonic bias field. Although in this case the combined signal recorded on the wire will have small variations corresponding to the bias frequency, it will have short time average values which are nearly proportional to the instantaneous magnitudes of the audio signal. The small variations are eliminated because any practical reproducer will not respond to the bias frequency. This being the case we can analyze the performance of the system during recording as follows: Referring again to figure 3, the positive peak values of the resultant field are projected up to the residual flux density curve. The corresponding residual flux-density values are plotted on the time axis on the right as curve A. (The construction for the second positive peak is shown.) The negative values are found in a similar manner and are plotted as curve B. The sum of curves A and B represents the residual flux density. If self-demagnetization could be neglected, this would represent the flux signal recorded on the tape. Some distortion is still present, but it has been greatly reduced from what it would have been without the bias field. Some further reduction could probably be obtained by a more judicious choice of audio and bias signal levels.

The distortion with high-level audio signals cannot be reduced by adjustment of the bias because this distortion is due to the upper bend of the residual flux density curve. Any increase in the bias field beyond that giving minimum distortion with low-level audio signals only results in deterioration of the high-frequency response and reduction in the length of the linear portion of the overall

transfer characteristic. It is desirable to have the linear portion of the overall transfer characteristic as long as possible in order to have as large a dynamic range as possible.

4. Reproducing.

After leaving the recording head, the tape passes over the playback head and is wound up on the take-up reel. (See figure 1.)

The recording may be monitored by playing it back as it passes over the playback head, or for later reproduction the reels may be interchanged and the tape passed over all three heads again but with all erasing, biasing, and recording power shut off. By the use of a continuous loop of tape rather than two reels, it is possible to compare almost instantaneously the signal to be recorded with the signal played back. The signal being recorded is impressed on an oscilloscope or on a speaker amplifier at the same time as it is impressed on the recording amplifier; the signal played back may be simultaneously impressed on another oscilloscope, or by means of a two-way switch the two signals may be impressed alternately on the oscilloscope or alternately on the speaker. The only delay in the reproduction is the time required for the tape to pass from the recording gap to the reproducing gap. It is interesting to note that when music and speech containing normal components out to 15000 cycles are compared in the A-B test, as it is called, the reproduction is almost indistinguishable from the original, even to an expert ear, at a tape speed of 30 inches per second. However, when a single audio tone is fed in from an oscillator, the reproduced signal is easily distinguished from the original by its distortion, either by the ear or on the oscilloscope. The reason for the marked difference

in the results of these tests is not yet fully understood.

CHAPTER III

FREQUENCY RESPONSE

1. General.

Magnetic recording is a phenomenon depending on current. The field intensity in the recording gap is nearly directly proportional to the magnetomotive force of the coil and this magnetomotive force is directly proportional to the current in the coil. The current in the coil is made practically independent of the frequency of the input signal voltage by using a series resistance which is large compared to the reactance of the coil. With constant input voltage this should result in nearly the same value of field intensity in the gap for all frequencies within the audio range if no recording filter is present. This being so, and ignoring for the moment the serious demagnetization effect which takes place with short magnets, the magnitude of the residual flux density should be independent of frequency. The length of the individual magnets is inversely proportional to frequency. Hence as the frequency increases the individual magnets become shorter. Because the flux lines must pass through the surface of the tape and through the air or other medium to a pole of opposite polarity, the surface density of the lines increases in direct proportion to the frequency, even though the maximum internal density across the sectional area of the tape may remain constant.

2. Recording.

The recording process differs from the reproducing process in that in the latter all elements operate in an essentially linear fashion while in the former the operation of the recording medium is

decidedly nonlinear. This greatly complicates analysis of the recording process. Without detailed analysis, however, it is possible to show qualitative correlation between the field distribution and the performance of a recording head.

When a signal is recorded on a magnetic medium, the process consists essentially of subjecting each element of the medium to a peak value of magnetizing force so related to the signal that the flux remaining in the element is proportional to the instantaneous value of the signal. The proper relation between the signal and the peak magnetizing force is established by the use of the high frequency bias field. In order that the flux remaining in the element may depend only upon the peak magnetizing force, it is essential that the element be subjected to no subsequent reversals of magnetizing force which are comparable in magnitude with its coercive force.

Measurements on typical recording media show that the coercive force is roughly one-half the maximum applied magnetizing force when the medium is working below saturation. Thus, after an element of the medium has been subjected to a certain magnetizing force, subsequent applications of magnetizing forces having perhaps one-fourth this value would have little effect on the flux remaining in the element. According to this reasoning, then, the portion of the field of a recording head which is important in the recording process is that part in which the magnetizing force is greater than about 20 or 30 percent of the maximum value of the magnetizing force.

In order that an element of the recording medium shall not be subjected to a reversal of magnetizing force when recording signals of high frequency, it is necessary to remove the element from the

influence of the recording field in a time equal to or less than approximately half the period of the highest frequency to be recorded. In practice this is accomplished by having the field of the recording head decrease as rapidly as possible in the direction in which the medium leaves the head and by moving the medium with sufficiently high velocity. When these conditions are not met the medium is subjected to one or more reversals of magnetizing force, partial erasing takes place, and the high frequency response of the system is impaired.

The manner in which the magnetizing force applied to an element builds up to its peak value is relatively unimportant. The reason for this is that the flux remaining in each element of the medium is for practical purposes determined by the maximum magnetizing force to which it has been subjected. This means that the shape of the field of a recording head is relatively unimportant in the region where the field applied to an element of the medium is increasing to its maximum value as the element moves through the head.

Figure 5 shows the field distribution of an experimental recording head. Figure 6 shows frequency response curves measured using this head for recording and a conventional head for reproducing. The upper curve represents the response obtained when the recording wire was traversing the head from right to left, and the lower curve from left to right as referred to figure 5.

It is evident that as the wire traverses the head from right to left the recording field builds up slowly to a maximum and then drops abruptly. The shape of the frequency response curve measured under these conditions is indistinguishable from that measured with

a conventional recording head, with the remainder of the elements of the system unchanged. Thus the slow buildup of the recording field and the large irregularity in the decay of the field have no appreciable effect on the recording process.

On the other hand, when the recording wire traverses the head from left to right, as referred to figure 5, the recording field builds up rapidly and drops slowly. The lower curve of figure 6 represents the frequency response measured under these conditions. It is evident that about an octave has been lost in the high-frequency region. This loss is attributed to the erasing action which takes place when the medium is subjected to several reversals of decreasing magnetizing force while within the influence of the recording field.

3. Reproduction.

The time rate of change of the lines leaving the surface of the tape at a north pole and returning through the magnetic circuit of the reproducing head to a nearby south pole determines the value of electromotive force induced in the playback head. The maximum rate of change for a constant total number of lines is thus directly proportional to frequency. This means that for constant recorded flux, output should rise linearly with frequency at the rate of 6 db per octave. Experiment shows this to be true only within a given range of frequencies the lower limit of which is determined by the point at which the rising characteristic emerges from the noise and hum to give a satisfactory signal-to-noise ratio. Neglecting demagnetization the upper portion of the frequency spectrum is affected by the air-gap width of the playback head according to the following equation:

$$E = K B_m S_r \sin \left(\frac{\pi l_g}{\lambda} \right) \quad * \quad (1)$$

At low frequencies the quantity $\sin \frac{\pi l_g}{\lambda}$ is almost linearly proportional to the frequency, and the output for constant input should rise as the rate of nearly 6 db per octave. At higher frequencies, the quantity $\sin \frac{\pi l_g}{\lambda}$ is not proportional to the frequency, and at a frequency such that l_g is equal to $\frac{\lambda}{2}$ the output reaches a maximum then falls to zero when l_g equals λ . The voltage again increases to a maximum when l_g equals $\frac{3\lambda}{2}$ and again falls to zero when l_g equals 2λ and so forth.

The quantity l_g , in the foregoing equation, is the effective gap width rather than the actual one. This distinction is necessary because of the fringing effect that takes place at the gap; the effective gap width is always greater than the physical one.

The effect of using gaps of different widths for the playback head is shown in figures 7 and 8. The frequency for which the physical gap width is a full wave length is shown in each case, and in both cases it can be seen that the frequency for which the effective gap width is a full wave length is lower. For the long gap there is slightly better correlation between the calculated and the measured values of frequency at which maximum response occurs than with the short gap. There are two reasons for this. In the first place, the percentage increase of the effective gap width due to fringing is less for a wide gap than for a narrow one. In the second place, with a fairly wide gap the demagnetization effect at the frequency of the first maximum is negligible,

* See List of Symbols, Page vi

whereas with a short gap this demagnetization effect reduces the output at higher frequencies and hence tends to lower the frequency at which the first maximum occurs. It is apparent, however, that as small a gap as possible is desirable in order to place the first minimum well beyond the audible range leaving a simple curve which is subject to compensation for flattening the overall response.

The effect of demagnetization on the response as the frequency rises is shown by the steady decrease in magnitude of the successive maxima. It would appear that there must be a compromise point in gap width somewhere between the small value which would (if demagnetization could be ignored) place the first maximum at the upper limit of the audio spectrum, and a larger value which would give a response curve whose first maximum occurs at a much lower frequency, but which is much less affected by demagnetization. In practice, however, it is found desirable to make the gap as small as possible, since the smallest gap built to date, $\frac{1}{2}$ mil, causes the first maximum to occur in the neighborhood of 4000-10000 cycles, depending on the tape speed. So far it has been impractical to make the gap any smaller.

It is desirable in gaining an understanding of the operation of a reproducing head and in designing heads for improved performance to be able to calculate the frequency response from a measurement of the field distribution. A method for accomplishing this follows: The field distribution curve of figure 10 was obtained by exciting the coil of the head (figure 9) with a known current and measuring the voltage in the exploring coil. By the reciprocity theorem it would be possible to interchange the current and the voltage; that is, if the same current were used to excite the exploring coil, the same

voltage would be read across the coil of the head. Under these conditions the exploring coil can be considered to be a source of magnetic potential difference acting over the effective length of the coil. If the effective length is sufficiently small, the exploring coil can be considered to be the source of a certain magnetic potential difference per unit length; that is, a magnetizing force, applied at a given point. Knowing the voltage induced in the coil of the head with this applied magnetizing force, and knowing the frequency and the number of turns in the coil, it is possible to calculate the flux in the pole pieces of the head resulting from a certain magnetizing force applied at any point along the path of the recording medium.

Noting that the curve of figure 10 exhibits symmetry about the center line of the gap and approximate local symmetry about the small peaks on either side of the gap, the curve can be represented by the following empirical expressions: *

$$f(x) = Ae^{-\alpha_1 x} \quad \text{for } 0 \leq x \leq a \quad (2)$$

$$f(x) = -Be^{-\alpha_2 (c-x)} \quad \text{for } b \leq x \leq c \quad (3)$$

$$f(x) = -Be^{-\alpha_3 (x-c)} \quad \text{for } c \leq x \leq d \quad (4)$$

$$f(x) = Ae^{\alpha_1 x} \quad \text{for } -a \leq x \leq 0 \quad (5)$$

$$f(x) = -Be^{-\alpha_2 (x+c)} \quad \text{for } -c \leq x \leq -b \quad (6)$$

$$f(x) = -Be^{-\alpha_3 (-x-c)} \quad \text{for } -d \leq x \leq -c \quad (7)$$

* See List of Symbols, Page vi

Assume a sinusoidally magnetized tape to be drawn through the slot of the reproducing head at an arbitrary constant velocity, the wavelength and amplitude of the sinusoidal distribution being arbitrary. The effect of each element of tape in sending flux through the pole pieces of the core can be found by multiplying the magnetizing force produced by the element of tape by the ordinate to the field distribution curve at the point where the element is situated. Applying the principle of superposition, the total effect of the tape in sending flux through the pole pieces of the core can be found by integrating the effects of all the elements whose influence is appreciable.

Neglecting demagnetization, the applied magnetizing force may be taken as

$$m = M \sin \frac{2\pi}{\lambda} (x - vt) \quad (8)$$

The flux through the core of the head is then

$$\phi = M \int_{-d}^{+d} f(x) \sin \frac{2\pi}{\lambda} (x - vt) dx \quad (9)$$

or, integrating and combining terms;

$$\phi = 2M \sin \frac{2\pi}{\lambda} vt \left[B \frac{-\frac{2\pi}{\lambda}(\alpha_2^2 - \alpha_3^2) \sin \frac{2\pi c}{\lambda} + (\alpha_2 + \alpha_3) \left\{ \left(\frac{2\pi}{\lambda} \right)^2 + \alpha_2 \alpha_3 \right\} \cos \frac{2\pi c}{\lambda}}{\left\{ \alpha_2^2 + \left(\frac{2\pi}{\lambda} \right)^2 \right\} \left\{ \alpha_3^2 + \left(\frac{2\pi}{\lambda} \right)^2 \right\}} - A \frac{\alpha_1}{\alpha_1^2 + \left(\frac{\pi}{\lambda} \right)^2} \right] \quad (10)$$

To establish a relationship between the coefficients A and B, consider a unit pole to be moved along the path of the recording tape from a point far outside the head on one side to a point far outside the head on the other side and back to the starting point by a path well removed from the head. Since there has been no net change in the magnetic potential, the net area between the curve $f(x)$ and the x-axis must be zero.

Thus

$$\int_{-d}^{+d} f(x) dx = 0 \quad (11)$$

Substituting for $f(x)$ and integrating, we have

$$B = \frac{A}{\alpha_1} \frac{\alpha_2 \alpha_3}{\alpha_2 + \alpha_3} \quad (12)$$

Making use of (10) and (12) and the fact that

$$e = N \frac{d\phi}{dt} (10^{-8}) \quad (13)$$

the voltage induced in the coil of the head is

$$e = 4\pi(10^{-8}) NMAf \cos 2\pi ft \left[\left\{ \frac{\alpha_2 \alpha_3}{\alpha_1} \right\} \frac{-\frac{2\pi f}{v}(\alpha_2 - \alpha_3) \sin \frac{2\pi ft}{v} + \left\{ \left(\frac{2\pi f}{v} \right)^2 + \alpha_2 \alpha_3 \right\} \cos \frac{2\pi ft}{v}}{\left\{ \alpha_2^2 + \left(\frac{2\pi f}{v} \right)^2 \right\} \left\{ \alpha_3^2 + \left(\frac{2\pi f}{v} \right)^2 \right\}} - \frac{\alpha_1}{\alpha_1^2 + \left(\frac{2\pi f}{v} \right)^2} \right] \quad (14)$$

If $f(x)$ may be assumed symmetrical about the small peaks on either side of the gap,

$$\alpha_3 = \alpha_2$$

and (14) becomes

$$e = 4\pi (10^{-8}) \frac{NMA f \cos 2\pi f t}{\alpha_1} \left[\frac{\alpha_2^2 \cos \frac{2\pi f c}{v}}{\alpha_2^2 + \left(\frac{2\pi f}{v}\right)^2} - \frac{\alpha_1^2}{\alpha_1^2 + \left(\frac{2\pi f}{v}\right)^2} \right] \quad (15)$$

Frequency-response curves have been calculated using (14) and (15) with values of the constants determined from the data plotted in figure 5. There was good agreement between the curves obtained from the two equations. Since (15) is the simpler of the two and is adequate to illustrate the principles involved, it will be used in the discussion that follows.

The values of the constants used in (15) are as follows:

$$\begin{aligned} \alpha_1 &= 375 \\ \alpha_2 &= 17 \\ c &= .14 \text{ inches} \\ v &= 24 \text{ inches per second} \end{aligned}$$

The empirical field-distribution curve obtained when these constants are substituted in (15) and the measured field distribution are shown in figure 10(b) and (c) plotted to expanded scales. The frequency-

response curve calculated with (15) is shown in figure 11 together with a measured frequency response curve for the same head.

The characteristics of the frequency response curve can be accounted for by considering (15). At very low frequencies each term in the brackets is nearly equal to unity, and the difference between them is very small. Thus the voltage induced in the coil of the head is very small for frequencies corresponding to wavelengths which are large compared with the dimensions of the head.

As the frequency increases, the first term in the brackets oscillates and decreases in amplitude. The second term remains practically constant throughout the low-frequency range. Thus, in the frequency region where the wavelength is of the same order of magnitude as the dimensions of the head there are undulations in the frequency response which gradually become imperceptible with increasing frequency. On the average, the response will increase about in proportion to frequency in the low frequency range. Because of the undulations, it will rise somewhat faster in certain regions, particularly at frequencies lower than that at which the first maximum occurs.

For frequencies corresponding to wavelengths which are small compared with the dimensions of the head, the first term in the brackets of (15) will be negligible. The response is then due entirely to the discontinuity at the gap. As the frequency increases and the wavelength becomes very small, the measured response reaches a maximum and then falls off rapidly. The calculated response behaves quite similarly.

The lack of agreement between the calculated and measured response in the high-frequency region is due to three factors; first,

the neglect of self-demagnetization; second, the finite dimensions of the exploring coil which made it impossible to determine the field-distribution curve in sufficiently fine detail for accurate calculations; and third, the inaccuracy in the empirical representation of the data in the respects that determine the performance of the head near its high-frequency limit.

The frequency response curve of a typical magnetic system without compensating filters will have the general shape shown in figures 12 to 14.

The rising characteristic in the lower part of the spectrum is due to the fact that for a recording made at constant recording current the voltage induced in the winding of the playback head is directly proportional to

$$\frac{d\phi}{dt}$$

where ϕ is the recording flux linking the coil. Since this quantity increases directly with the frequency, the voltage is doubled when the frequency is doubled, and since

$$db = 20 \log_{10} \frac{V_2}{V_1} \quad (16)$$

$$db = 20 \log_{10} 2 \quad (17)$$

and the output rises 6 db per octave. This result in a straight line when plotted on semilog paper, as shown in figures 12 to 14.

The linear characteristic is modified at the lower end of the spectrum by the fact that the system and the tape have a definite

noise level below which the output level cannot drop. When the frequency drops to a point where the useful signal output approaches instead of approaching zero approaches the noise limit, which it reaches at zero frequency. Hence the lower limit of the useful frequency range is limited by the noise level of the system. A factor contributing greatly to this system noise is 60- or 120- cycle hum from the power supply or filaments. It is obviously essential, therefore, to keep this hum factor at a minimum level in order to obtain good low frequency response.

The upper frequency limit is determined by factors already discussed. The problem presents itself of so modifying the tape response curve as to present a flat characteristic throughout the useful frequency range.

It has been accepted practice in some other fields to record with a characteristic rising toward the high frequencies and compensate in the reproducing circuits to give an overall flat response. It has been found that some increase in the signal-to-noise ratio can be accomplished by this practice. In the case of magnetic recording, however, it is not feasible to use a comparable amount of such recording and playback compensations because at the speeds which are desirable for recording the frequency response at the higher audio frequencies falls off very rapidly. However, even in this case enough recording compensation can be used to make the overall response flat within a specified frequency range. Playback compensation for increasing the high frequency response is not desirable, because the objectionable noise has been found by rough measurements and by listening to occur at medium and high frequencies. Playback compensation

would amplify the noise as well as the signal.

Due to the fact that, in reproduction, the low-frequency response of the system is inherently lower than the response in the middle frequency range, some form of bass compensation must be used. It is not feasible to use sufficient recording compensation to obtain even flat overall response because the tape will not accept the resulting large recording signals without overloading. A sufficient reduction of the recording level to permit the use of recording compensation would result in a less favorable signal-to-noise ratio. On the other hand, playback compensation is feasible because the amount of noise in the low-frequency range is small.

The system is supplied with two filters, one of which flattens off the linearly rising portion and the other of which raises the falling characteristic at the high end in such a way as not only to flatten the response there, but also to raise the high frequency limit. Each of these filters must have such a characteristic with frequency that when it is added to the uncompensated characteristic and the characteristic of the other filter a flat resultant response curve is obtained.

The low-frequency filter is inserted in the playback portion of the system, between the preamplifier and the final playback amplifier. It consists of a resonant circuit similar to that shown in C, figure 15, resonant in the neighborhood of 50 cycles and with a Q such that its characteristic falls linearly at the rate of 6 db per octave over the linear tape range. As is shown in figure 15, it has another resonance point at a much higher frequency, which causes it to begin

to curve upward again at about the same point that the uncompensated curve, A, begins to fall off from the linear rise.

This filter is inserted in the playback section because since it is resonant at about 50 cycles it accentuates 60-cycle hum. If it were put in the recording section or even ahead of the playback pre-amplifier the hum would be amplified several times more, and would be more noticeable when played back.

The high-frequency compensating filter is placed in the recording circuit. A typical recording circuit is shown in B, figure 15. The audio signal is fed across the 750-ohm resistor and the bias is applied through the transformer shown. The filter consists of the .01 microfarad condenser in series with the recording head, together with the 3900 ohm resistor with which it is paralleled. The resistor serves to give the filter circuit the proper Q for the desired slope characteristic; it must also serve to provide constant current recording for the portion of the spectrum which is not to be compensated by this filter. The size of this resistor must therefore be a compromise.

This filter is resonated well beyond the high-frequency peak of the uncompensated tape curve, as is shown in curve B, figure 15. The result obtained by combining curves A, B, and C is shown in figure 16, and the actual overall response obtained using a system with these components is shown in figure 17. With judicious choice of components it is possible to obtain a very flat characteristic over the useful frequency range, and to extend materially the upper frequency limit of the system.

At the higher audio frequencies, the effect of self demagnetization

is pronounced and for a given frequency increases rapidly as the tape speed is reduced. This results in a reduction in the high frequency response. The high frequency response also deteriorates when the quantity $\frac{l_g}{\lambda}$ lies between $\frac{1}{2}$ and 1. In a practical system the tape speed is made such that this occurs near the upper end of the working frequency range.

Both of these effects are important, but the experimental determination of the relative reduction in response caused by either is difficult.

Assuming a given fixed wavelength recorded on the tape the demagnetizing effect and the effect of the gap length will be constant and will be independent of the tape speed. Both the output voltage and its frequency will then be directly proportional to speed. Knowing this, it is easy to find the constant current frequency response at any tape speed from the response curve at a known speed by a simple graphical construction. A right triangle is drawn with its hypotenuse rising 6 db per octave. The length of the base is taken as the distance on the logarithmic frequency scale between two frequencies having the same ratio as that of the known speed to the speed at which the frequency response is desired. An example of this construction is shown in figure 18, where the lower curve represents the frequency response at 15 inches per second as obtained from the measured response at 30 inches per second. The lower curve is traced by the lower left-hand corner of the triangle as the tape is moved along the 30 inch curve and the base is kept parallel to the zero axis.

For a given medium, it is possible to modify the frequency response somewhat, especially at the higher frequencies, by changes in

the design of the recording head. However, small changes in the playback head have a much greater effect. The design of the playback head is very critical. The gap must be short in order to obtain good response at the higher audio frequencies. The material should have as high a permeability as possible at low flux densities. The eddy-current losses should be low in order that the high frequency response will not be impaired. The magnetic coupling between the recording medium and the head should be good in the immediate vicinity of the gap but should be as low as possible at the points of entry and exit in order to reduce the magnitude of the secondary or stray flux which may produce certain undesirable variations in the frequency response curve.

Let us consider the manner in which these variations are produced. Referring to figure 19, it can be seen that passage of the tape across the pole pieces on either side of the gap sets up an alternating magnetic potential between points C and D and at the same time another alternating magnetic potential is set up between A and B. The magnetic potential between C and D reaches a maximum effective value at a relatively low audio frequency. Alternate dips and peaks occur in the effective values of this magnetic potential at regularly spaced frequency intervals, depending on the wavelength recorded on the tape relative to the effective width of the reproducing head. The flux due to this magnetic potential is termed the "secondary" or "stray" flux.

There are two paths for this stray flux. One is directly across the head and through the gap. The other is from point C down through that pole piece, across the lower gap and up through the other pole piece to point D.

The alternating magnetic potential between A and B is the one which gives the useful response. There are also two paths for the flux produced by this alternating magnetic potential. One of these is directly across the front gap. The other is around the complete magnetic circuit in a counter-clockwise direction. Now consider the coils to be mounted as shown in figure 19. The useful component will increase with frequency according to the equation previously given. As mentioned above, the other component passes through several positive and negative peaks as the frequency changes over the audio frequency spectrum. The total response will then show peaks and dips which become less pronounced as the frequency increases. If the coils are moved to a higher position on the pole pieces, a similar response curve will result except that the phase of the electromotive force due to the stray field is reversed, causing the position of the dips and peaks to be interchanged.

In the design of permanent magnets, great stress is laid on the proper size and shape of the magnetic circuit so that the permanent magnet material may be used at or near the point of maximum energy. This makes the most efficient use of the costly alloys which are used for permanent magnets. Such a design is not possible for magnetic recording media, because the ration of length to width for the individual magnets which make up the recording varies from a large value at low frequencies to less than unity at the higher frequencies. The retentivity of the recording medium for a given tape speed determines the maximum value of the output voltage at the lower audio frequencies. At these frequencies the wavelength is relatively long and self-demagnetization is not serious. For this reason one would expect good

bass response for materials with high retentivity. A large number of experimental frequency response curves have shown this to be true.

The second magnetic characteristic which affects the frequency response to a very great degree is the coercivity of the material. The demagnetizing field intensity can be considered to be equal to the product of the demagnetization factor and the remanent flux density. The demagnetization factor increases in magnitude as the ratio of the length of a permanent magnet to its cross section decreases. Whether or not the flux density is greatly reduced because of the demagnetization factor depends on the demagnetization curve and especially on the value of the coercive force.

The effect of demagnetization is less with materials having high coercive force. It is generally considered to be true that a magnetic material which has high coercive force will also have low retentivity. This is especially true of many materials used in magnetic recording. This means that we may have to sacrifice some output voltage at the lower audio frequencies in order to extend the upper frequency range by use of a material which has high coercive force but lower retentivity.

CHAPTER IV

NOISE

1. Mechanical.

The factors contributing to background noise in magnetic recording are both magnetic and mechanical. The principal mechanical factors are variation in uniformity of the cross section of the recording medium, which causes irregular voltages to be generated, and transverse or longitudinal vibrations of the tape as it passes over the reproducing head. These vibrations may be produced either by an irregular recording surface or by non-uniform torque anywhere in the driving system, and may result in flutter as well as in background noise.

2. Magnetic.

The factors governing noise from magnetic sources are not yet completely understood. Magnetic noise increases in the presence of a recorded signal. This can be demonstrated by recording a sine-wave signal on the medium and filtering out the signal frequency and its harmonics in the reproducing system. The reproduced noise will have frequency components distributed throughout the filter passband, and their amplitude will increase with an increase in recording level, diminishing when an erasing field is applied. This noise is probably caused by the finite size of the elementary magnetic particles of the medium. A certain amount of such noise is not noticeable, being ordinarily masked by the signal. However, an excessive amount imparts a disagreeable fuzzy quality to the reproduction.

Equation 1 indicates that the noise voltage should increase with tape speed. Measurements show that the noise level rises about 6 db

each time the speed is doubled.

It was pointed out earlier that any magnetic recording system using direct current bias ordinarily leaves the recording medium magnetized even in the absence of an audio signal. In this case, the noise is particularly bad because there is no signal to mask it. Another effect which may contribute to the noise is so-called "cross-talk" or "printing". Printing is caused by magnetic fields in one layer of tape exerting a force on particles in the adjacent layer tending to orient them in accordance with those fields. It is possible for one turn of strongly magnetized recording medium to magnetize an adjacent turn. This re-recorded signal may show up as objectionable noise, particularly during quiet passages of a selection when it would not be masked by the desired signal. The higher the coercive force of the material, the less printing occurs; however, a material with high coercive force requires excessive erasing power.

Very little work has been done on printing as yet; however, one method of combating it which seems to offer possibilities is to put a coating of soft iron powder on the tape underneath the recording coating. This soft iron offers a path for magnetic flux from point to point and by decreasing the amount of flux passing from one magnetic layer to the adjacent one decreases printing. This process, however, is still in an experimental stage.

3. System.

In considering noise, that originating in the reproducing system should also be mentioned. The signal output from a high impedance reproducing head is of the order of only a few millivolts, which makes it necessary to use a large amount of amplification. The amplifier

must be carefully designed to minimize thermal noise and to be free from hum. In addition, the effects of strong electrostatic and electromagnetic fields on the reproducing head must be minimized by shielding or other means. The problem of eliminating hum is aggravated when playback compensation of the low frequencies is used. This is apparent from the fact that 15 or 20 db of compensation at 50 cycles is necessary in some cases for flat response.

There have been many general statements concerning the permanency of the records on magnetic media. Much more information than we have at present is needed before we can make well founded statements concerning the ability of the medium to retain indefinitely without loss. Experiments show that there is a loss of from 3 to 25 db in output from a given record during the first few playings. After this initial aging process there seems to be little further loss for a reasonable time and a reasonable number of playings. In general materials which have properties desirable from other viewpoints tend to show small loss with repeated playings. As far as is known, no great difficulty has been experienced on account of this effect.

Once the factors affecting the maximum signal and those affecting the noise have been determined, the problem of determining the effective signal-to-noise ratio remains. The effective signal-to-noise ratio depends not only upon the factors already discussed but also upon the frequency distribution of the noise, the frequency distribution of the speech or music to be recorded, and upon the amount of recording compensation and playback compensation.

CHAPTER V

FIELD MEASUREMENTS

1. General.

The following work was done on wire recording heads, but the general principles apply to tape recording as well, and this discussion is presented here because no similar work appears to have been done yet for tape recording heads.

The technique used in measuring the magnetic field depends upon the measurement of the electromotive force induced in a minute exploring coil as the coil is placed at various positions along the path of the recording medium. A schematic illustration of the type of head upon which most of the measurements were performed is given in figure 9(b). This is a conventional head having a high-permeability core, a close fitting slot for the wire, and a short air gap.

The mechanical setup used for positioning the exploring coil with respect to the head is illustrated in figure 20. It is evident from the figure that the position of the coil is fixed, and that the head is movable with respect to it. The exploring coil is the most critical part of the setup, and several were tried before a reasonably satisfactory coil was obtained. It is desirable to make the coil very small in order to determine the field distribution with as much detail as possible. The most satisfactory type of coil used consisted of a single turn on N. 45 Formex-insulated wire wound around a .0012 X 0.015 inch phosphor bronze strip. The leads from the coil were twisted tightly together for a distance of several inches to minimize the effect of stray fields.

A block diagram of the electrical setup for measuring the electromotive force induced in the exploring coil is shown in figure 9(a). A current of any desired amplitude and frequency is supplied to the head under test by the audio oscillator. The induced e.m.f. is amplified and measured with a wave analyzer tuned to the oscillator frequency. With this arrangement, voltages as small as 10^{-8} volt were detectable.

Since the permeability of the material enclosed by the exploring coil is practically that of free space (neglecting eddy-current effect) the flux linking the coil is proportional to the magnetic potential difference across the coil. Since this magnetic potential difference occurs over a very short fixed distance, the flux through the coil, and hence the voltage induced in the coil, can be considered to go proportional to the magnetizing force along the axis of the coil at the point where the coil is placed. Thus, if the exploring coil is placed at various positions along the path of the recording medium, a measure of the relative magnetizing force to which the recording medium is subjected at each point can be obtained. It is assumed that the field distribution is not appreciably affected by the presence of the recording medium in a practical case because the permeability of the recording medium is very small compared with the permeability of the core.

A typical graph of voltage induced in the exploring coil as a function of distance along the path of the recording wire is shown in figure 10(a). The large peak at the origin is obtained when the coil is in the air gap, and the smaller peaks when the coil is entering and leaving the slot. Measurements on different types of heads indicate that the shape of the field-distribution curve varies considerably with the design of the head. In particular, the shape of the small

peaks on either side of the curve shows large variations for different heads; this shape depending upon the configuration of the slot in the regions where the recording wire enters and leaves the head.

The current required to saturate the core of a head can be found by placing an exploring coil in the air gap, and measuring the induced voltage as a function of the exciting current. Correlation of the current required to saturate the magnetic circuit of the head with that required for recording at saturation levels on wires of known coercivity shows that saturation of the head is not appreciable for wires having coercivities less than 600 oersteds.

Magnetizing force as a function of frequency can be measured in a similar manner. What variation is found is due to resonance of the inductance of the coil with its own distributed capacitance. The variation is not necessarily detrimental, and for conventional heads is small in the audio frequency range.

No important variation in the shape of the field distribution curve has been found when the amplitude or frequency of the exciting current is varied or when bias current is present.

CHAPTER VI

TAPES

1. Description.

The tape now commonly used in magnetic recording consists of a nonmagnetic medium (paper or plastic) with a magnetic material applied, either by dispersion through the binder or by coating on one surface. The Germans, who were well ahead of the rest of the world in the development of tape recording, had three tape types in general use. These will be described briefly, as all American tapes are more or less patterned after them.

The first, type "C", consists of a cellulose acetate base, with a coating of nonmagnetic iron oxide in a nitrocellulose binder. It is still being produced extensively at Wolfen, Germany, for Russian applications. This tape is of good quality, uniform and of generally low noise level. Its one drawback is that unless kept in humidors it dries out and will then break easily.

Type "L" tape consists of a "luvitherm" (stretched) base with magnetite incorporated in it. Its manufacture has now been discontinued, as the plant at Glendorf which manufactured it has been taken for Russian reparations.

The third German tape, type "IG", consists of a "luvitherm" base with a magnetic dispersion coating. It was put into production at the end of the war. There are still uncertainties in manufacture, chiefly because of the nonuniformity of the base which is apt to stretch unduly.

Fe_2O_3 (red iron oxide) is normally considered to be non-magnetic,

but there are various crystal structures to the oxide, and the one used for recording is the "gamma" type. A test with the powder on a piece of paper with a magnet beneath gives exactly the normal iron filings reaction showing that it is unquestionably magnetic.

2. Manufacture.

The German processes for manufacturing tape are briefly as follows:

Type C: Cellulose acetate is dissolved in acetone, the solution after filtering is poured onto a film casting machine on a continuous copper belt 20 meters in length and about 55 centimeters wide. When the basic film is nearly dry a second layer is spread on consisting of magnetite dispersed in a cellulose acetone solution. The whole film is then removed after drying and cut into strips.

Type L. Equal parts of "Igelit PCU" and magnetite are mixed, finely ground and sifted. By passing four or five times through a heated rubber mill, the mixture forms a sheet which is subsequently calendered out to a thin film. Finally the film is stretched on a stretching unit at a ratio $1:2\frac{1}{2}$ ("luvithermed").

Type LG. As in the normal production of luvitherm tape, Igelit PCU with an addition of one percent titanium dioxide is hot milled. As in the manufacture of type L tape, it is sheeted out by means of a heated calender and luvithermed on a stretching machine. This film is then further processed on a film casting machine, developed by I. G. Farben, whereby a dispersion of magnetite in two parts tetrahydrofuran and MP 400 (copolymer of vinylchloride and vinylisobutyl ether) is spread on in a thin layer.

3. Testing.

A series of tests has been developed which at present is applied

to samples of new types of tape for the purpose of determining recording and reproducing properties.

The first test consists of taking a curve of output level versus input level for the system at a single frequency. Figures 21 to 24 inclusive show samples of this curve for various tapes. The curves were taken at a signal frequency of 700 cycles and using optimum bias voltage at a frequency of 76 kilocycles.

On each curve sheet is given a value of tape noise and one of system noise. The useful signal-to-noise ratio is obtained by determining the spread between the overload point and the tape noise. For example, the signal-to-noise ratio for the German type C tape from figure 22 is 68 db.

Before a figure for signal-to-noise ratio can have any meaning the band width of the reproducing system must be specified. In this particular measurement equipment, the high frequency cutoff was at 500 cycles, and a cutoff at 500 cycles was obtained at the lower end by means of a high pass filter in order to eliminate 60 cycle hum and its measurable harmonics. This was desirable because although hum affects the signal-to-noise ratio we are interested here only in the magnetic characteristics of the tape, which affect only random noise and not hum. This system permits the various tapes to be compared for signal-to-noise ratio on the basis of a fixed bandwidth. Since in a high quality system the useful lower level of output will be generally determined by thermal noise and hum, the signal-to-noise ratio will be directly proportional to the overload level, and hence knowledge of the signal-to-noise ratio. Figure 25 shows how the total harmonic distortion varies with reproducing level for various types of

tape. In taking the data for these curves, a General Radio 632A distortion meter was used, measuring harmonic distortion at 500 cycles. Optimum bias voltage was used in each case.

Figure 26 shows the variation of total harmonic distortion with reproducing level for various values of high frequency bias voltage. These curves are for German type C tape recorded and reproduced on German heads. They demonstrate the importance of determining the optimum high frequency bias value at a particular level. In this case the bias should be determined at a reproducing level of plus 24 db. The important thing is to select a bias value which can be duplicated and which furnishes the lowest overall distortion. This condition is obtained when the distortion rises very slowly with reproducing level up to a certain value and then breaks sharply. Figure 27 shows the variation of output level and harmonic distortion with bias voltage, again for German type C tape on German heads. Note that minimum distortion is given by the same bias as is required for maximum output -- a very desirable condition, and one achieved by none of the American tapes so far produced. (See for example figure 28.)

Figures 12 to 14 show variations of output with frequency for a given input with different types of tapes. The curves for German type C and DuPont MT-78 tapes were taken at 18 inches per second tape speed; the tape speeds for the other curves are shown on the curves.

It is clear that the tape speed is a major factor in determining the frequency response, but there are many other factors. Higher coercive force improves the frequency response by reducing the demagnetization effect when the wave length is short. This is shown best on figure 12. Hyflux tape has a much higher coercive force than

Brush or Scotch tape, and gives a better high frequency response. Thickness of the magnetic coating is another factor affecting high frequency response. The thinner the coating the better the response, but this improvement is obtained at the cost of a loss in signal level. The best compromise appears to be between one-half and one mil thickness. The width of the gap in the playback head is another factor influencing high frequency response. A smaller gap improves the high frequency response, but reduces the output. The best compromise is obtained when the effective gap width is slightly greater than the thickness of the nonmagnetic spacer between pole tips. This spacer is usually about $\frac{1}{2}$ mil in thickness.

CHAPTER VII

DRIVING SYSTEMS

1. General.

As in any other sound recording system the quality of the recording is adversely affected by any variations in the speed of the medium, either in recording or during playback. A tape driving system developed by Masterson will be described in order to show some of the problems involved in eliminating this speed variation which shows up in the reproduction as a variation in the frequency, either at a slow rate, in which case it is commonly known as "wow" or at a rapid rate, when it is called "flutter".

In this driving system, figure 29, a three-phase synchronous motor drives a flywheel to which is attached integrally a short shaft-like projection known as a capstan. A rubber roller bears against the capstan normally, being pivoted on the end of a metal arm and held in place by a spring. The tape is fed between the capstan and the rubber roller. The capstan drives the roller and the friction of the rubber drives the tape.

The tape reels are mounted one on each side of the magnetic heads and well below them. Each reel is mounted on an arm whose center of pivot is halfway between the inner and outer limits of the tape. Concentric with each reel is a pulley. These pulleys bear on a cloth belt which is driven by the same motor that drives the xq capstan. Both pulleys and hence both reels tend to be driven in the same direction by the light friction between the belt and the smooth pulleys. The reel on which tape is being wound, or "take-up" reel, is rotated

in such a direction as to take up the tape, and the friction is varied with the amount of tape on the reel in such a way as to maintain the tension on the tape substantially constant. This is due to the variation of the lever arm on which the tape exerts its pull, as the amount of the tape on the reel increases.

An identical action takes place with the other or "hold-back" reel, except that the friction exerted by the pulley against the cloth belt tends to wind up the tape and, therefore, resists the tension to the driving capstan and roller. The system is mechanically designed so that the tensions on the two sides of the capstan and roller are always substantially the same, and the net result is that the driving capstan and rubber roller are not subject to tension from the tape. This means that they serve only to feed the tape from one reel to the next and require very little force for the purpose. This means that since the tape tension is held constant throughout the reel, the tape does not stretch and speed variation due to this cause is eliminated.

Using a drive system of this type the principal remaining source of speed variation has been found to be sliding friction along the heads or against any guiding surfaces. This is similar in nature to the chattering obtained by rubbing one's finger across a pane of glass. It was found that reducing the guide surface to the minimum necessary to prevent damage to the tape reduced the flutter somewhat. The greatest reduction, however, was obtained by replacing the light pulley at the input to the erase head with a heavy flywheel which serves to damp out the chatter.

CHAPTER VIII

CONSTRUCTION OF HEADS

The best American heads that have been built to date are patterned on German heads used on broadcast transcription equipment. The principal differences between the American and the German heads are differences in inductances and in choice of material to fill the gaps. The German recording head, for example, had an inductance of about 90 mh. The American model was built with identical dimensions, but with about 12 mh inductance. This was done to make it possible to use a higher bias frequency (100 kc) than the Germans had used. With the high inductance it was impracticable to obtain enough bias current at the higher frequency.

The three heads are essentially similar in construction; the only differences lie in the inductances, the widths of the gaps, and the materials to fill the gaps.

Each head has two pole pieces, made up of about 80 laminations of mu metal 3 mils thick, cemented together to form a stack about 270 mils thick. A laminated structure is necessary in order to hold eddy currents to a minimum at the high frequencies involved, particularly in erasing and biasing. Even with this pole structure, it is found with some tapes that if a field strong enough to erase them is supplied the erasing head gets too hot to touch.

The two faces formed by the ends of the laminations form magnetic gaps in what would otherwise be a complete ring of mu metal. These faces must be very carefully lapped in a lapping block especially constructed for the purpose. The faces must be very nearly parallel

so that there will be no perceptible variation in the widths of the gaps. Such a difference or taper has its greatest effect in the playback head, whose gap is of the order of $\frac{1}{2}$ mil wide. Here a small error in the parallelism of the surfaces forming the edges of the gap results in a large percentage variation of the gap width.

Each pole piece is now covered with a layer of insulating paper and fitted with terminal boards, then wound with the proper size and number of turns of wire. The pole pieces are then mounted in the brackets with the proper thickness of material in the gaps and fastened securely. The surface composed of edges A and B, figure 19, is lapped lightly so as to afford a smooth surface against which the tape may rub without excessive wear. The two windings are connected and two leads brought out for connection to the external circuit. The heads are then mounted on a panel and shielded to prevent radiation and pickup.

The individual gaps are made as follows:

Erase head: Front gap, about 10 mils sheet copper. The wide gap insures a relatively long period of erase action on an individual tape element; the copper has high conductivity and therefore large eddy currents are induced in it, which force flux up and out of the gap and into the tape. The back gap is 10 mils wide, usually filled with plastic, as no eddy currents are desired here.

Recording head: Front gap, 1 mil sheet duralumin. The narrow gap is required for good recording characteristics especially at high frequency. The back gap is 10 mils wide, filled with plastic. The wide gap here serves to give a taper between the top and the bottom of the front gap. This concentrates the flux at the top of

the gap and results in more of the flux being sent into the tape.

Pickup head: Front gap, $\frac{1}{8}$ mil, sheet duralumin. Here, even more than in recording, a narrow gap is required for satisfactory high-frequency response. The back gap is 14 mils of mu metal. The mu metal is used here in order to present a low-reluctance path for the fields induced by the moving tape.

CHAPTER IX

CONCLUSION

Studies in connection with magnetic recording systems lead to the following general statements concerning the performance of present experimental systems and possible future improvements in magnetic recording systems.

Reasonable fidelity is possible at the present time. In order to get a system with low distortion, careful control of the bias field is necessary. The correct value of the bias field varies within wide limits for different recording media.

The signal-to-noise ratio which can be attained at present is superior to that which is obtained from the ordinary shellac disk recording. It is not yet so good as can be obtained from the new vertically-cut vinylite transcriptions. It is expected that improvement in the signal-to-noise ratio will result from further studies in connection with noise and that this will lead to improved recording media and improved design of the recording and reproducing heads.

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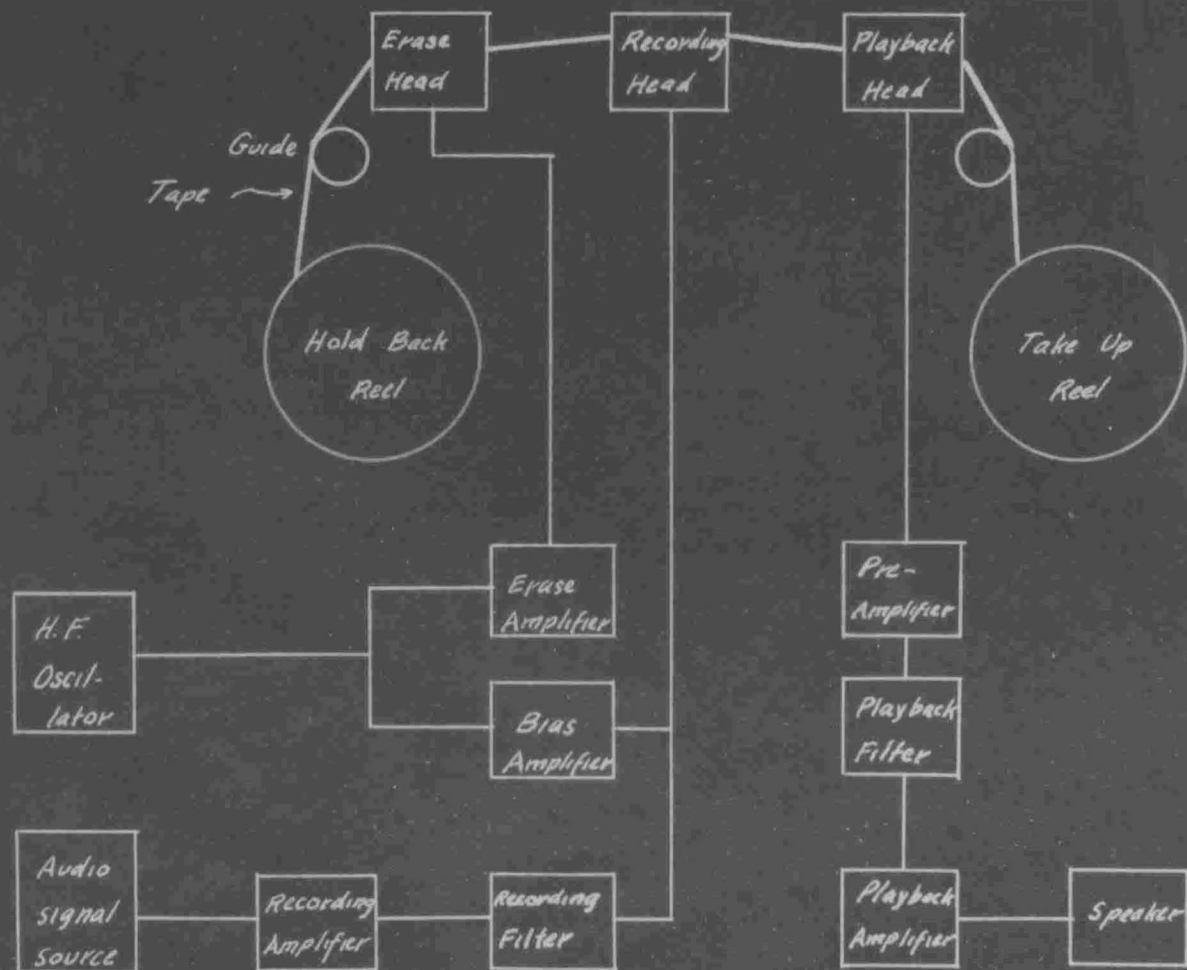


Figure 1

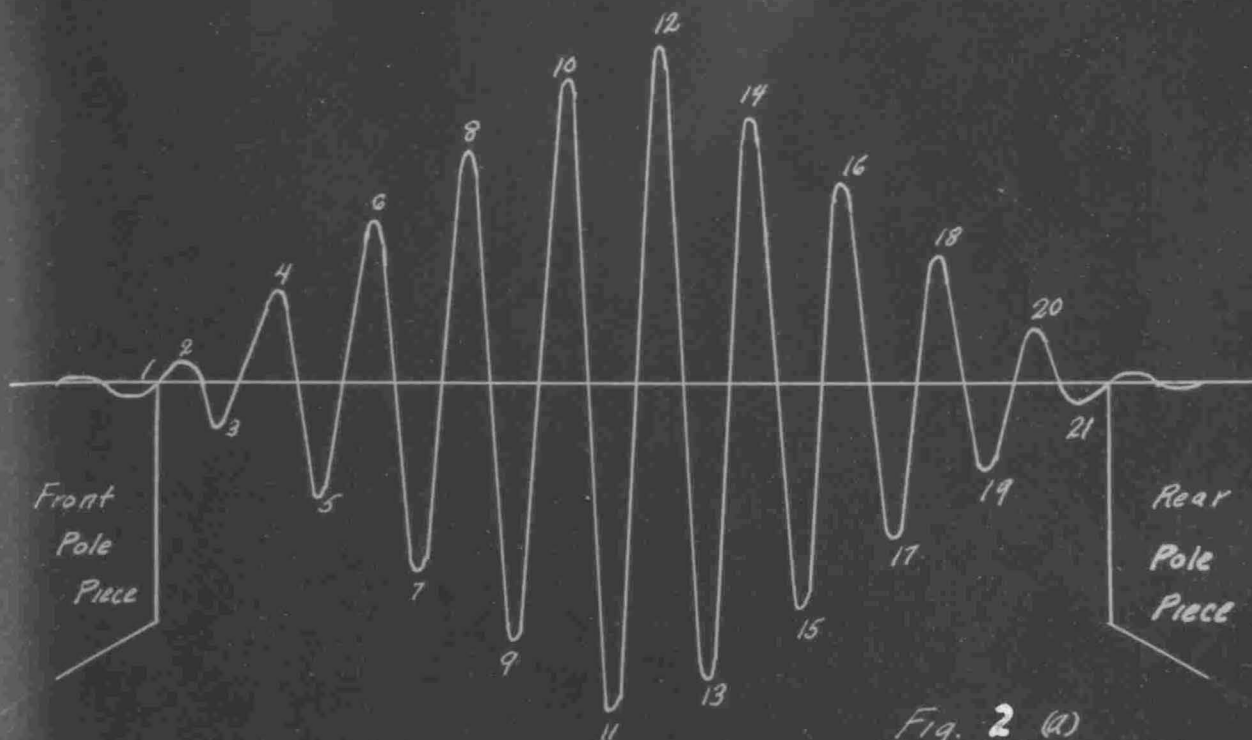


Fig. 2 (a)

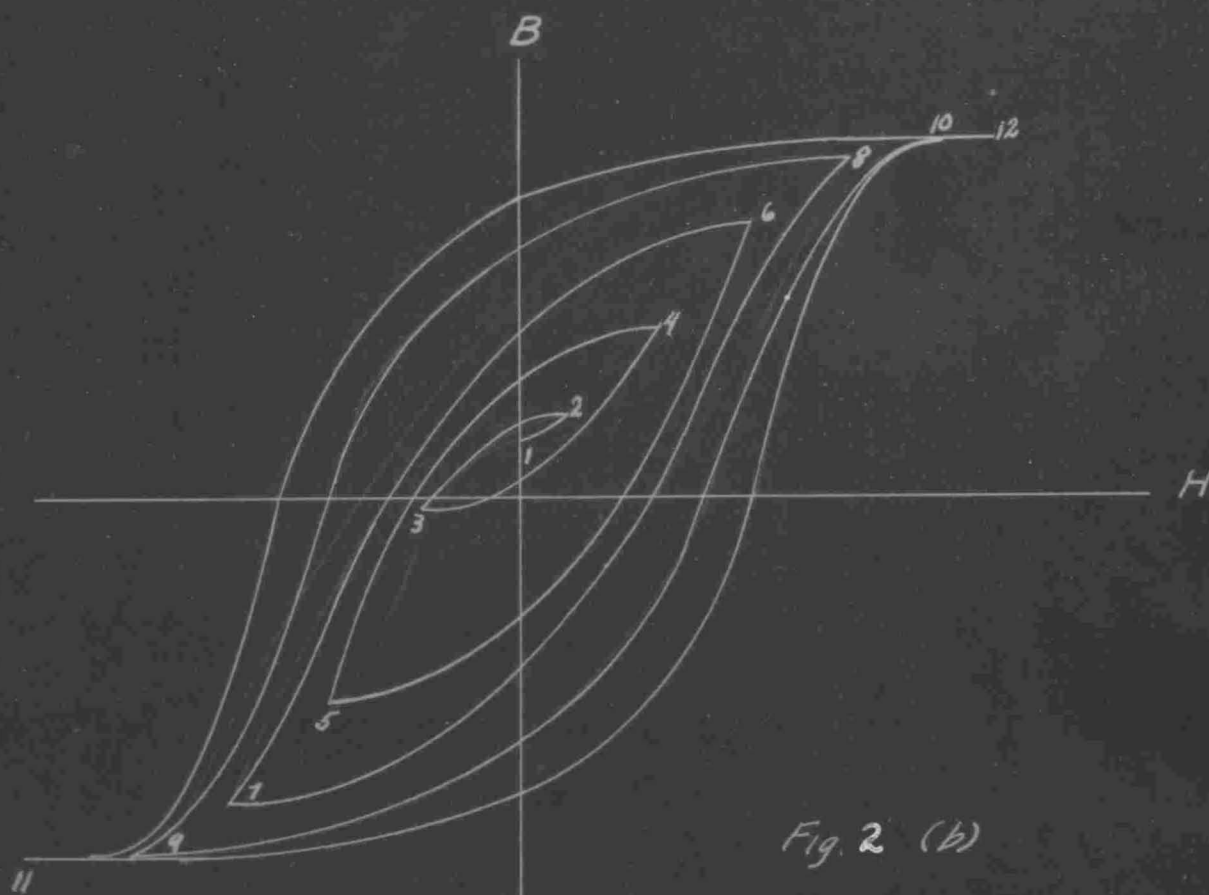


Fig. 2 (b)

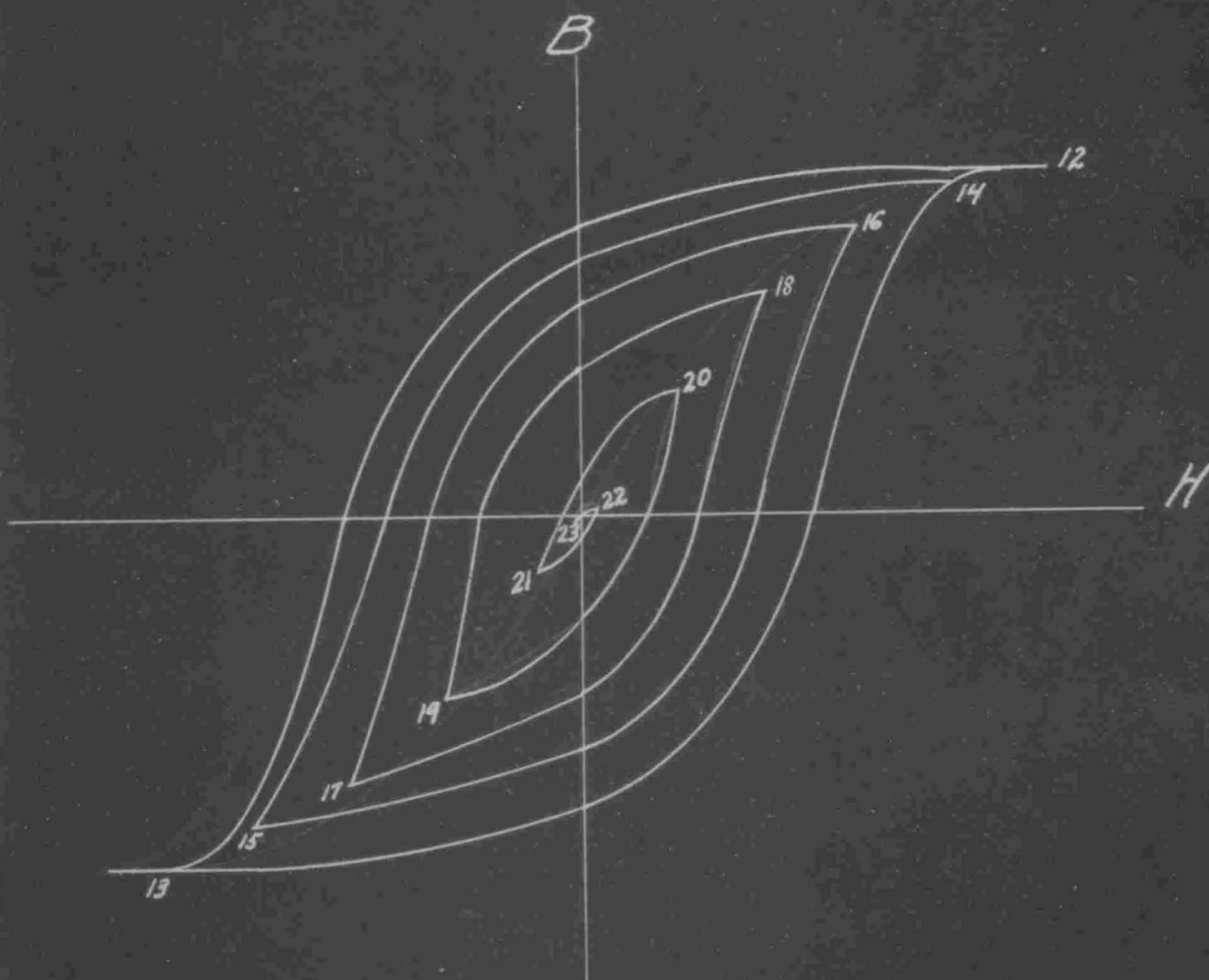


Fig. 2 (c)

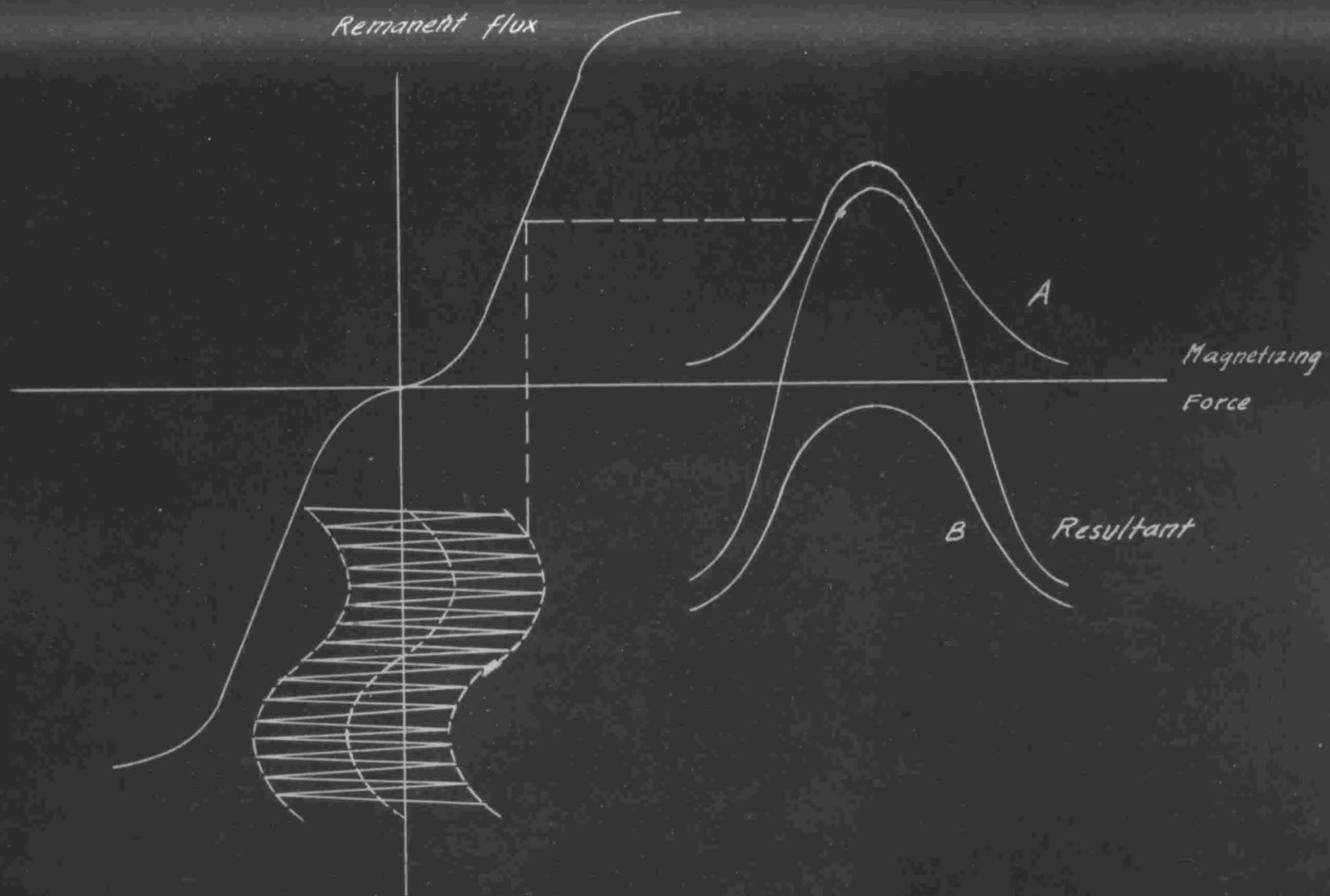
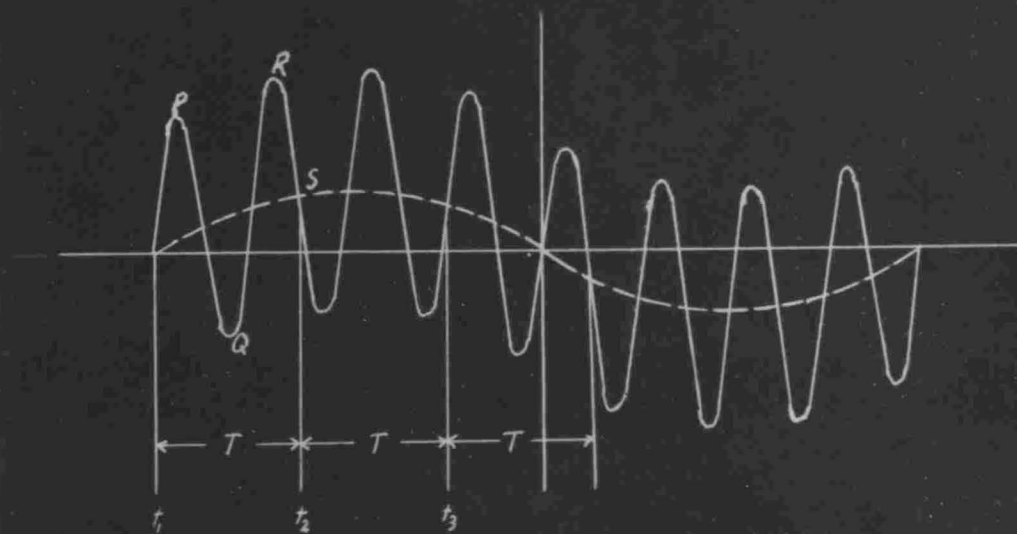
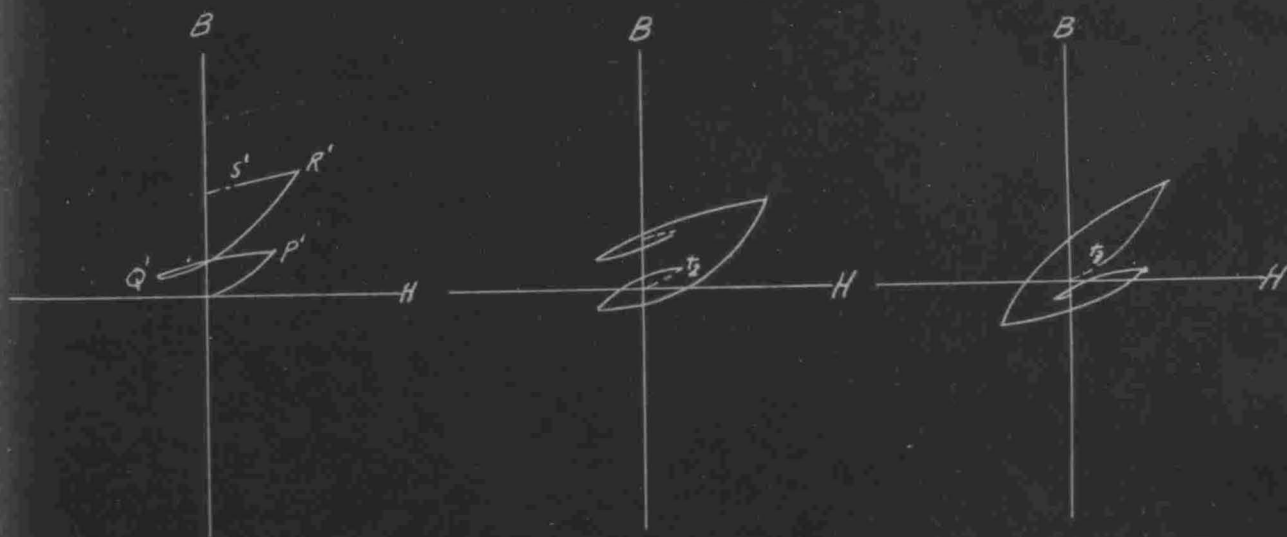


Fig. 3



(a)

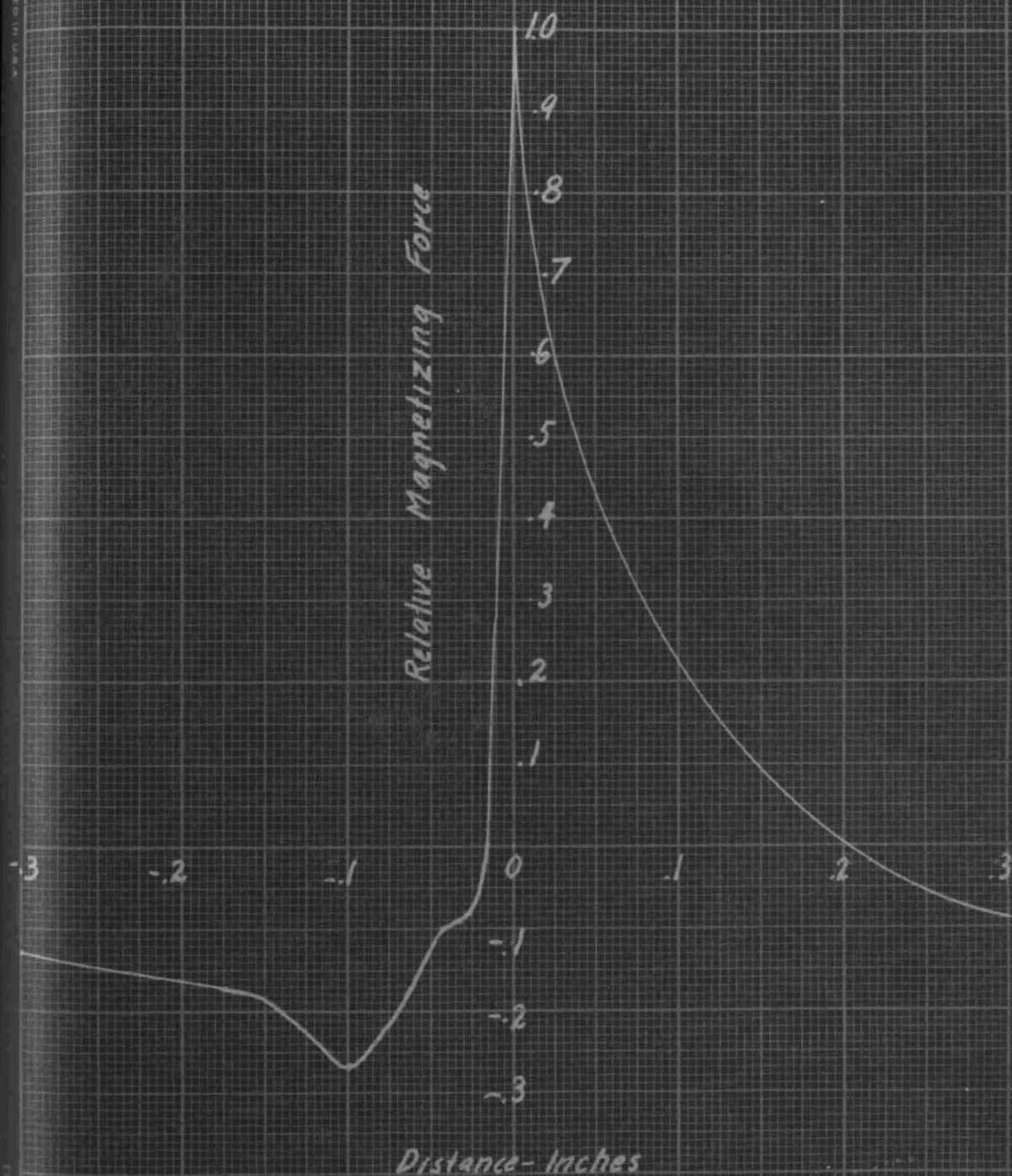


(b)

(c)

(d)

Fig. 4



Relative Magnetizing Force as a Function of Distance
Along the Path of the Recording Medium for an Experi-
mental Head.

Fig. 5

Output in db 85

40

30

20

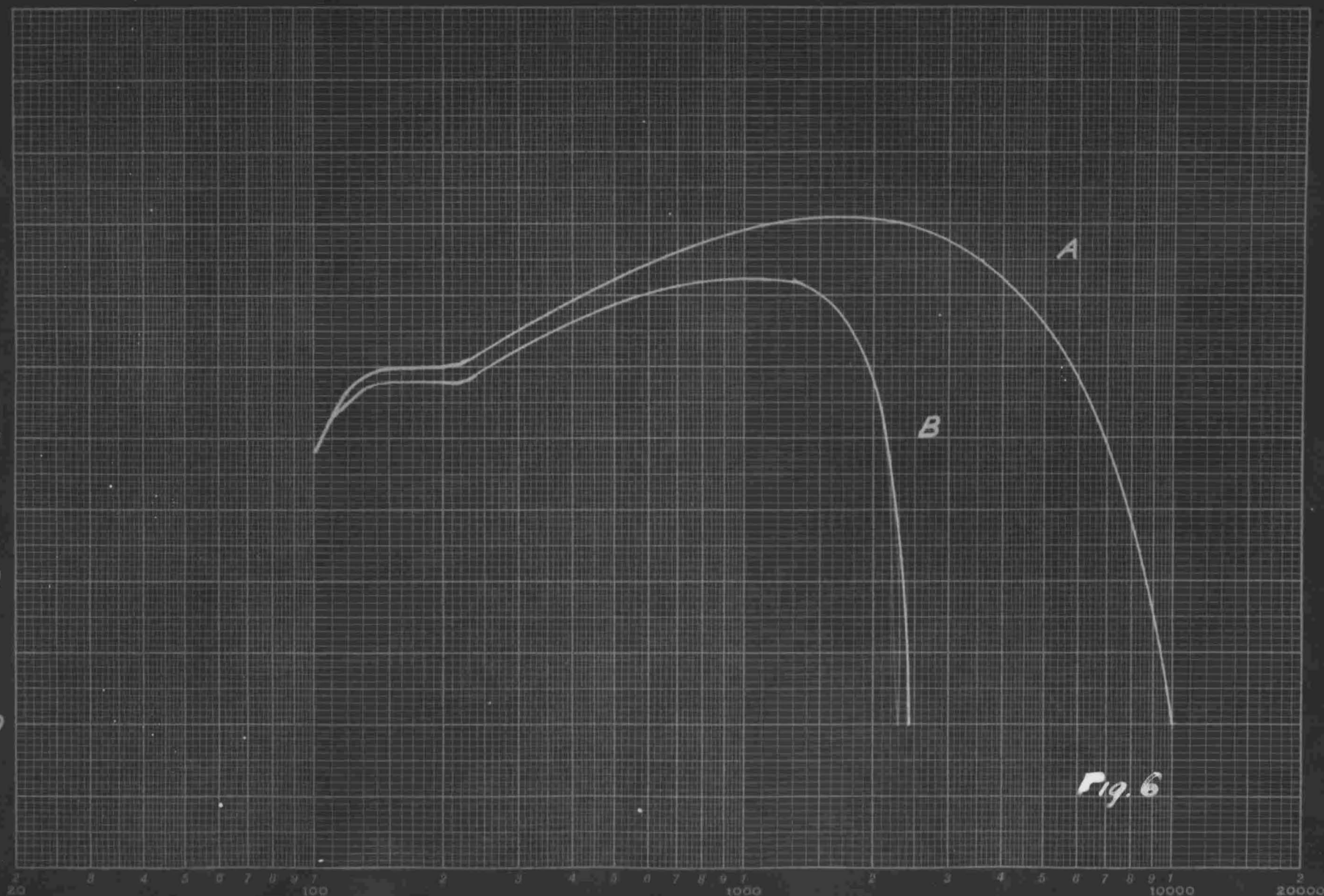
10

0

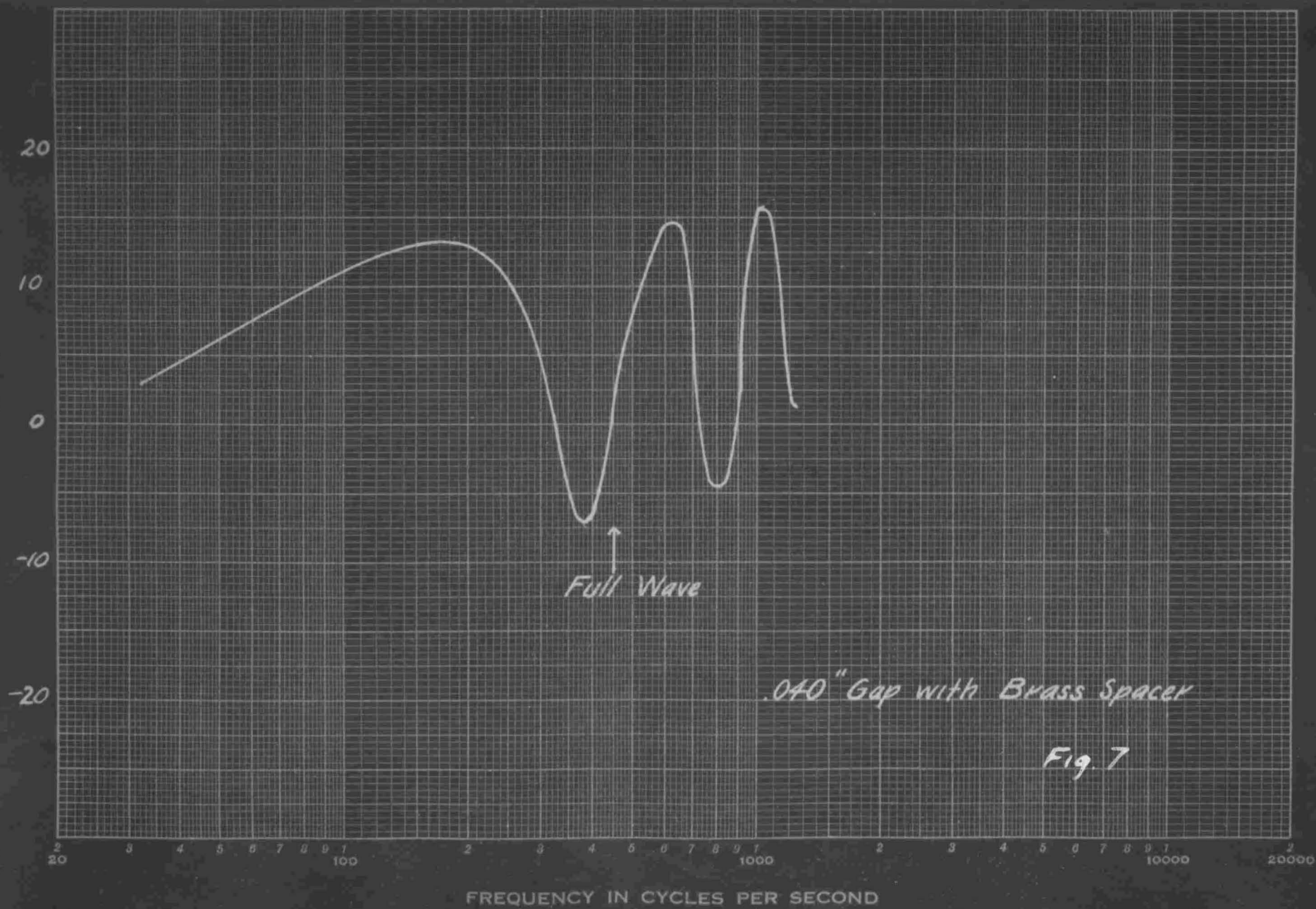
A

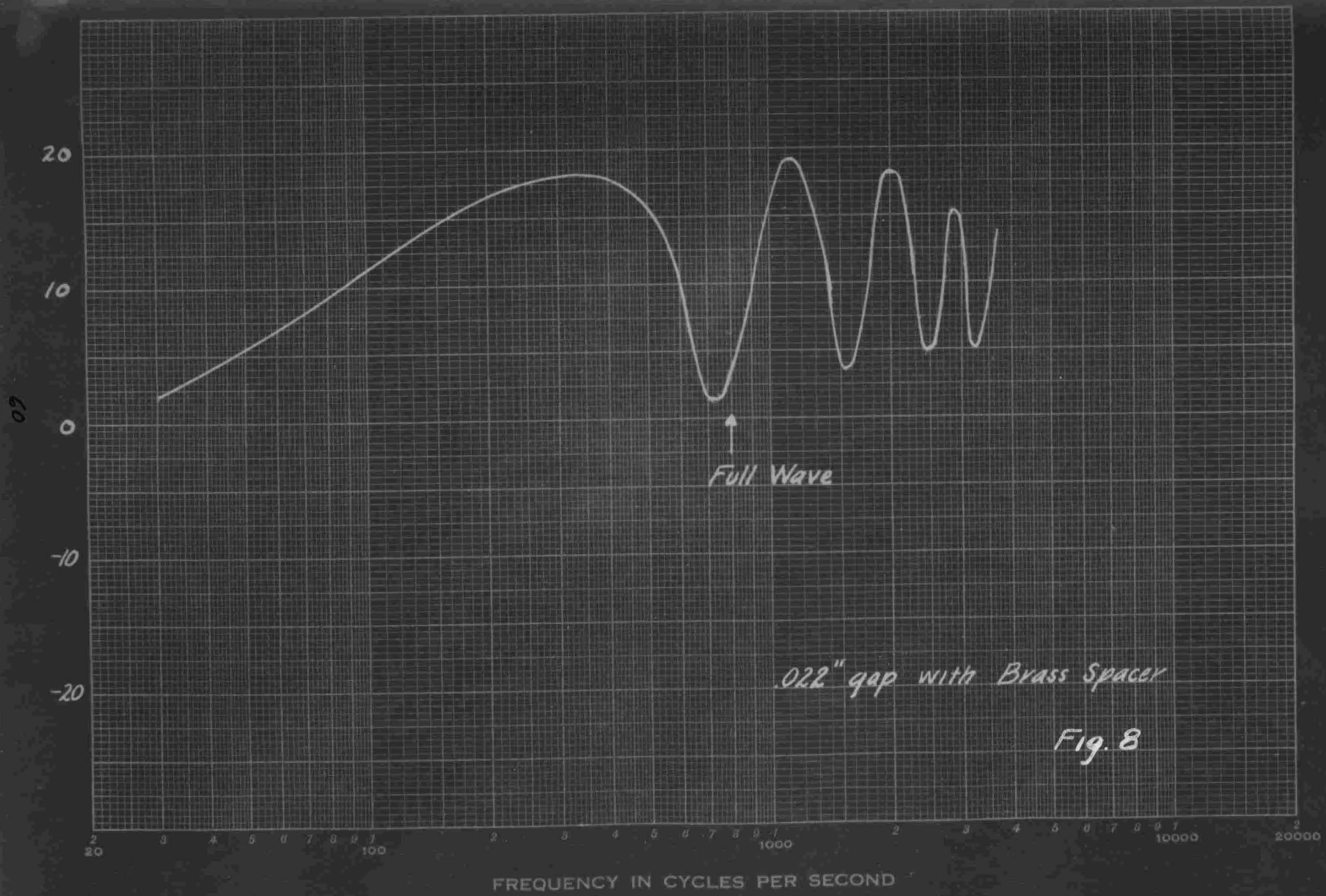
B

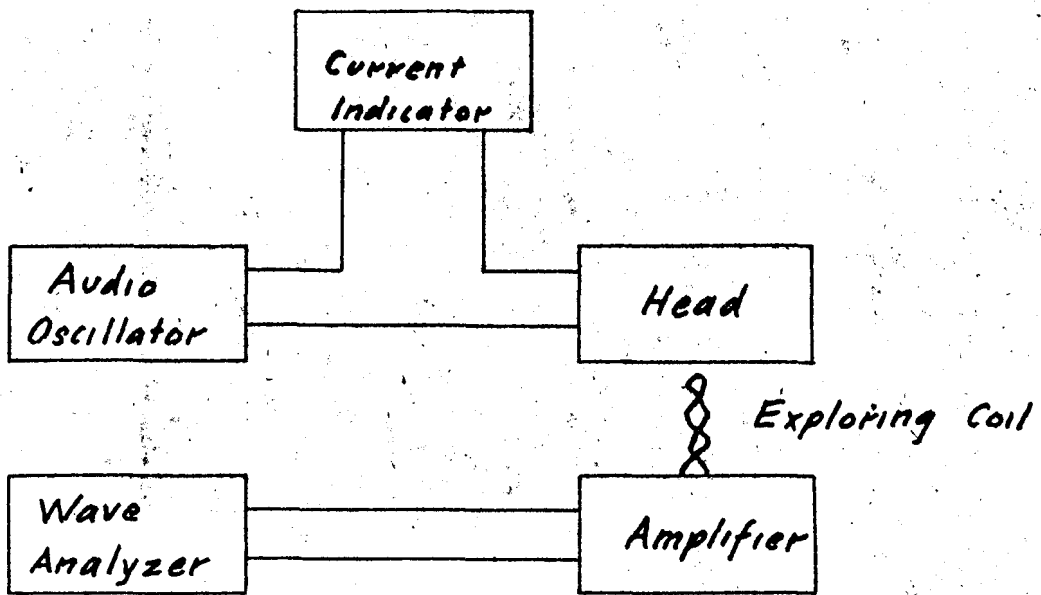
Fig. 6



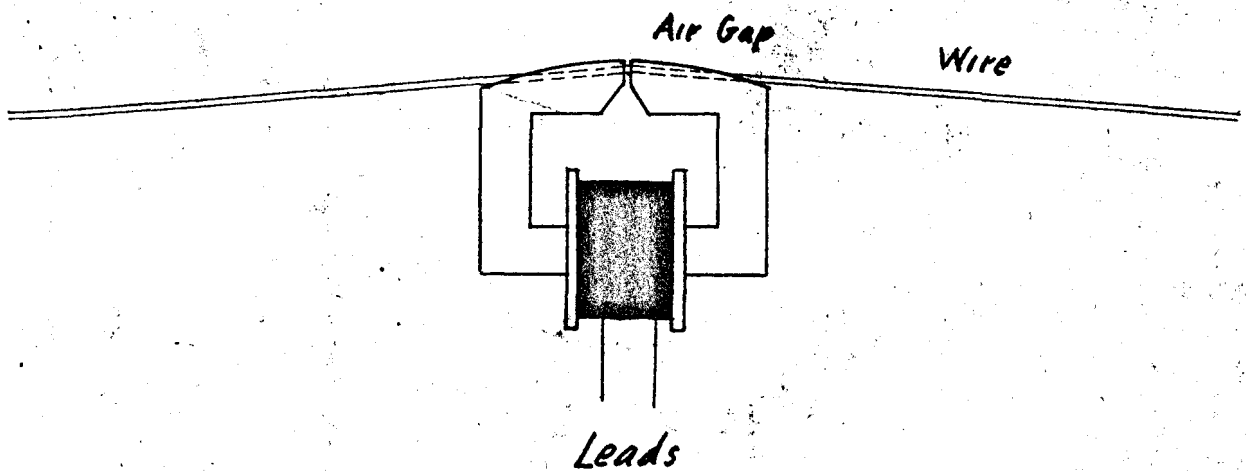
FREQUENCY IN CYCLES PER SECOND





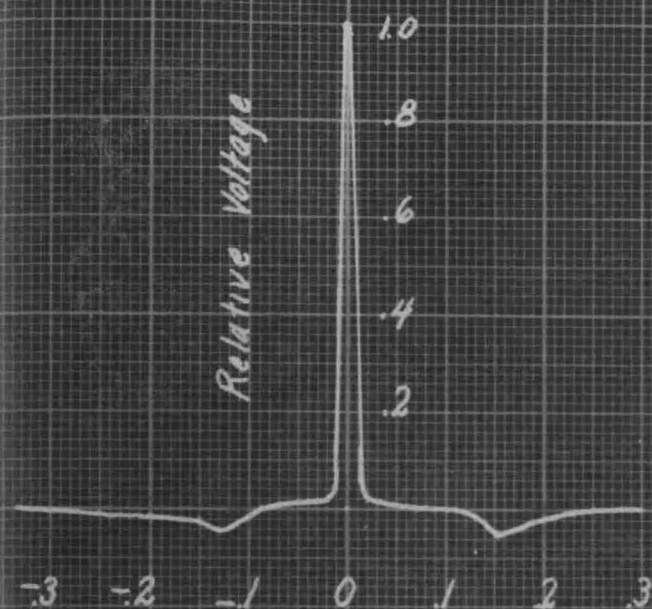


(a)



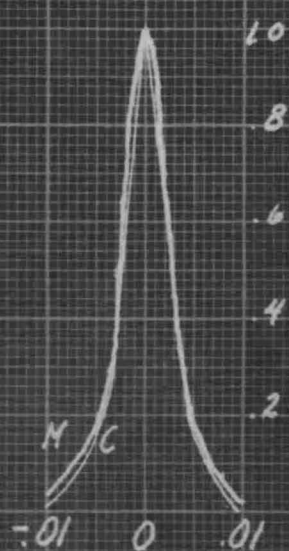
(b)

Fig. 9



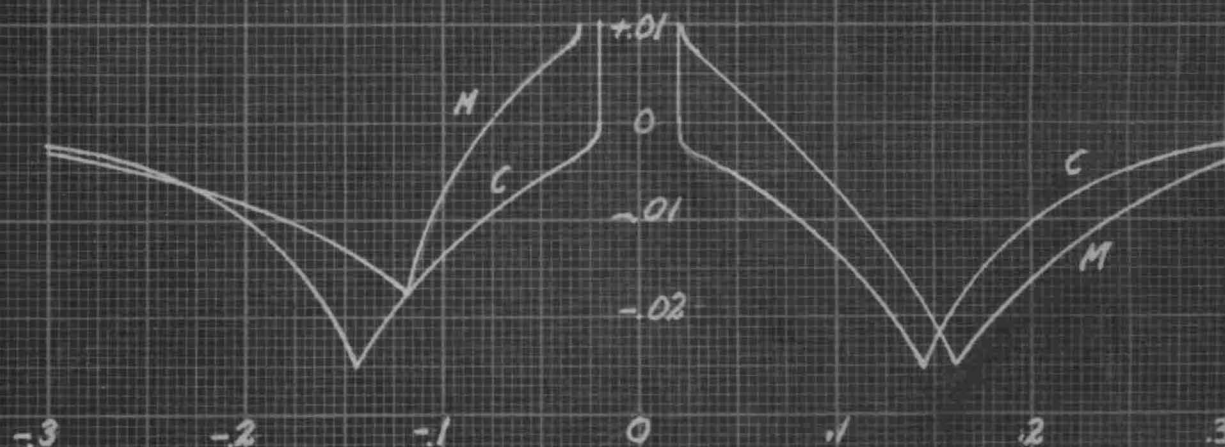
Distance - Inches

(a)



Distance - Inches

(b)



Distance - Inches

(c)

Fig. 10

63
Relative Response in db.

40

30

20

10

0

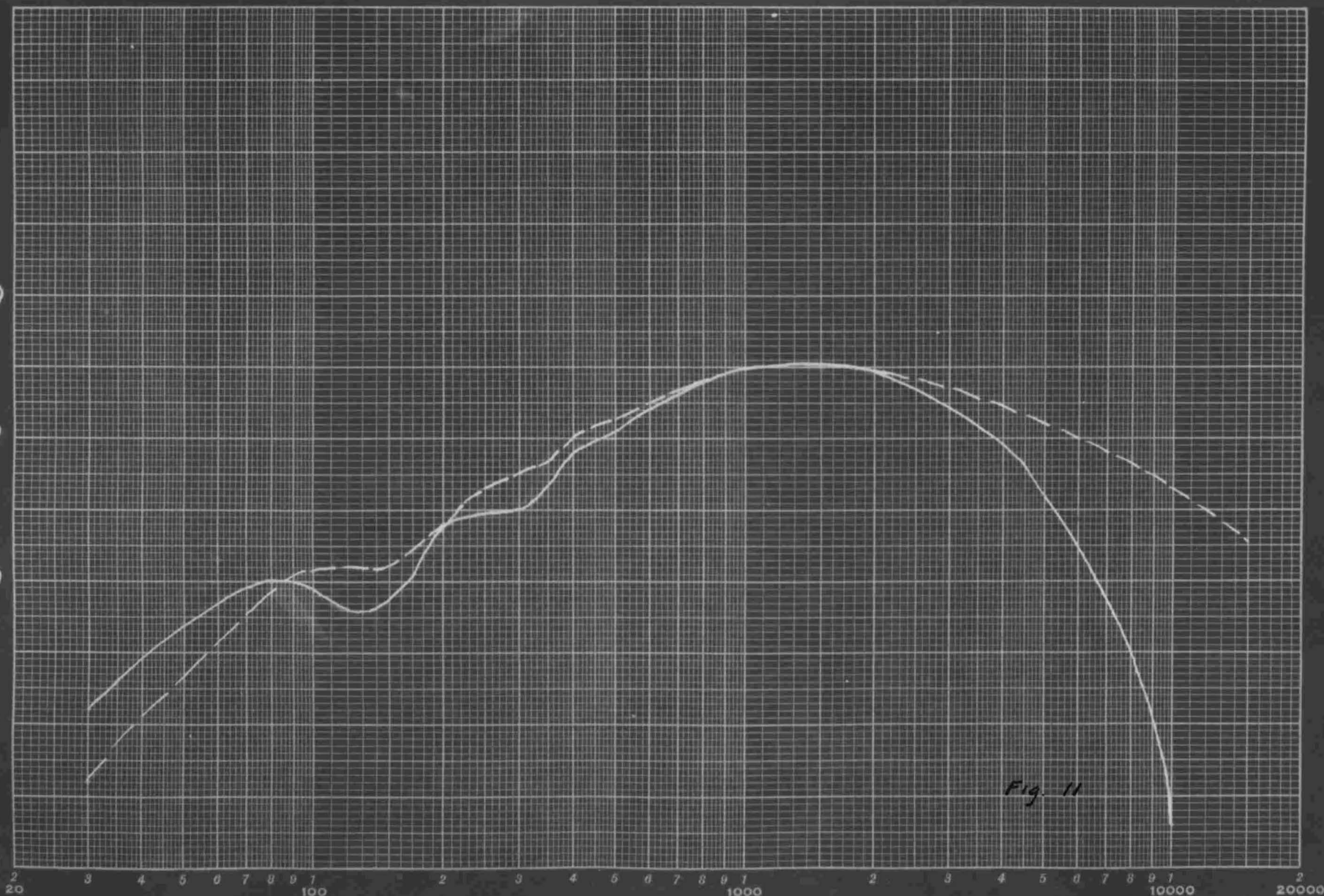
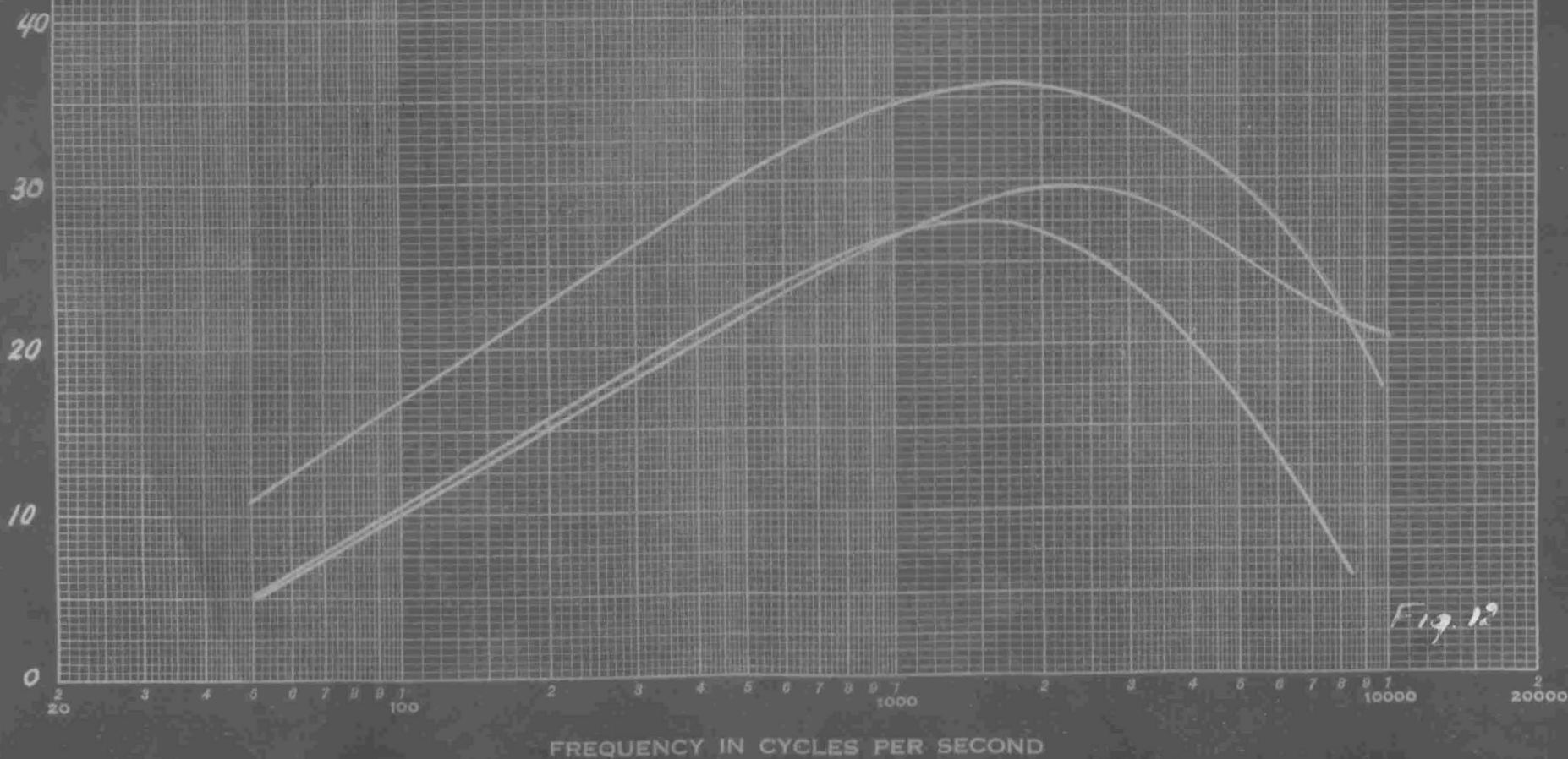


Fig. 11

FREQUENCY IN CYCLES PER SECOND

Frequency Response of
Scotch, Hystlux, and
Brush Tapes



Output, db

30

20

10

0

Frequency Response

DuPont MT-78 Tape

18"/sec

Fig. 13

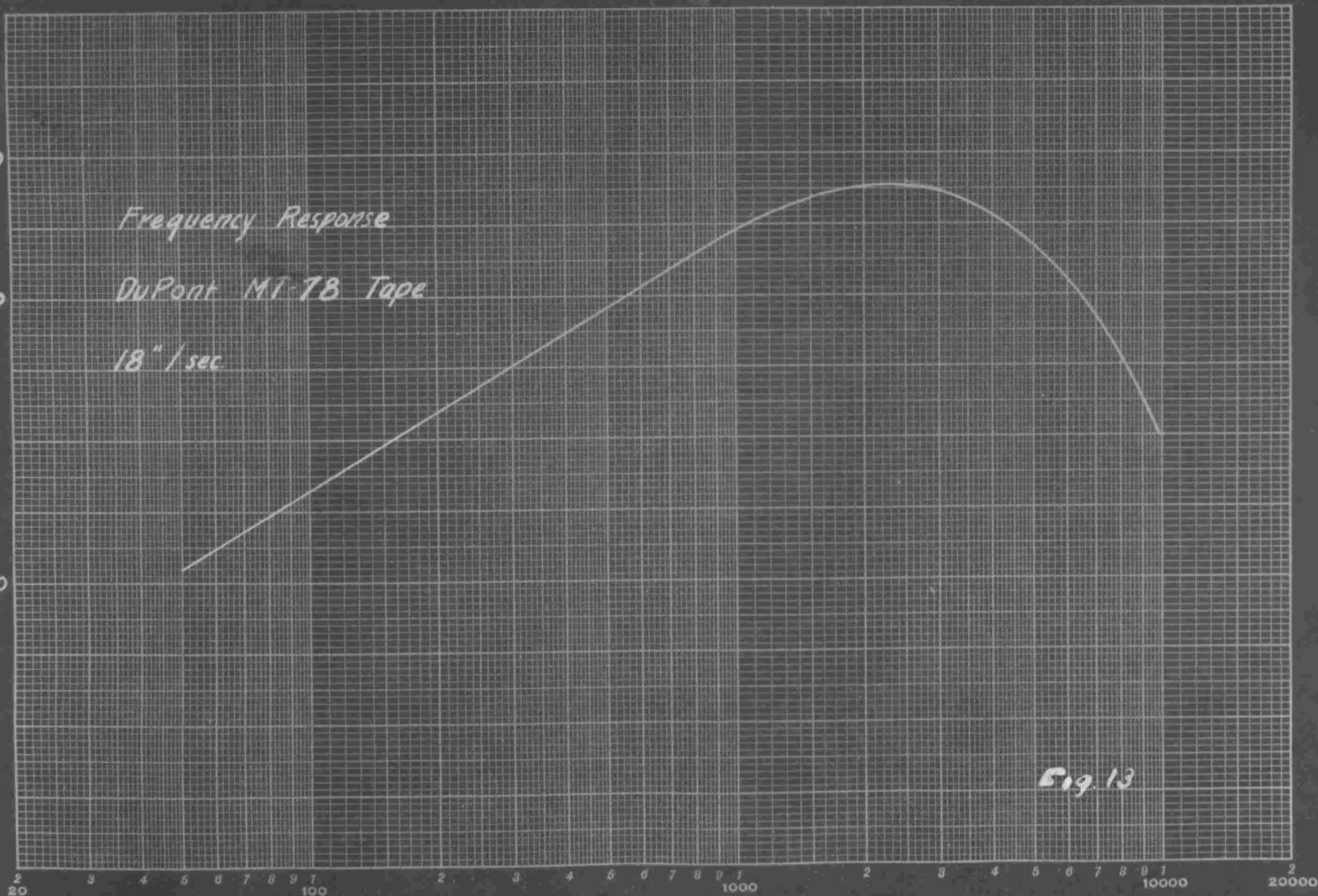
20 30 40 50 60 70 80 90 100

2 3 4 5 6 7 8 9 10 1000

2 3 4 5 6 7 8 9 10 10000

20000

FREQUENCY IN CYCLES PER SECOND



Output in db

Frequency Response of "Scotch"
Sound Recording Tape at
Various Speeds

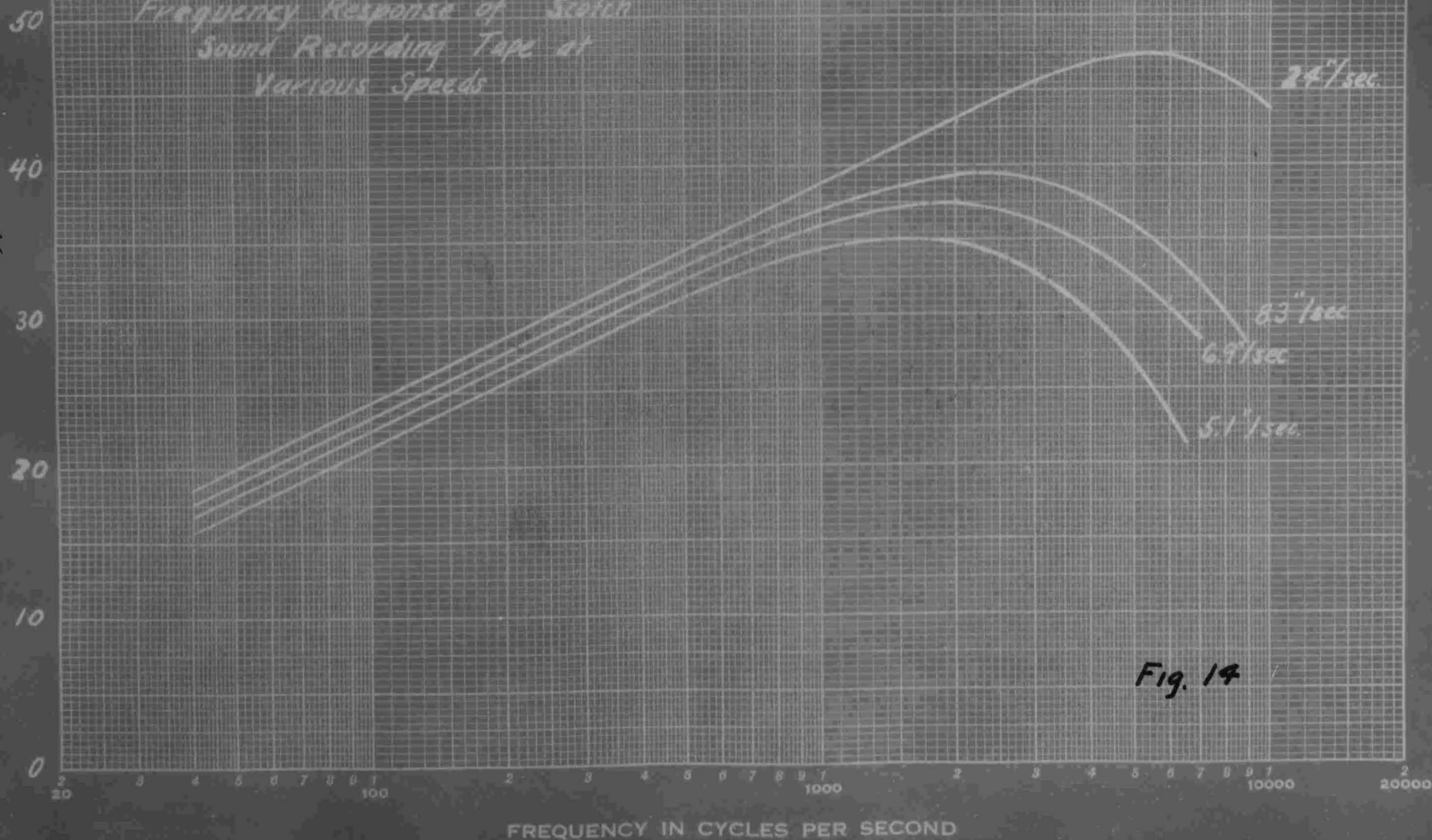


Fig. 14

Output Level, db.

Frequency Response Curves

- A. Tape, System Uncompensated
- B. Recording Compensator Alone
- C. Playback Compensator Alone

Tape Speed 15"/sec.

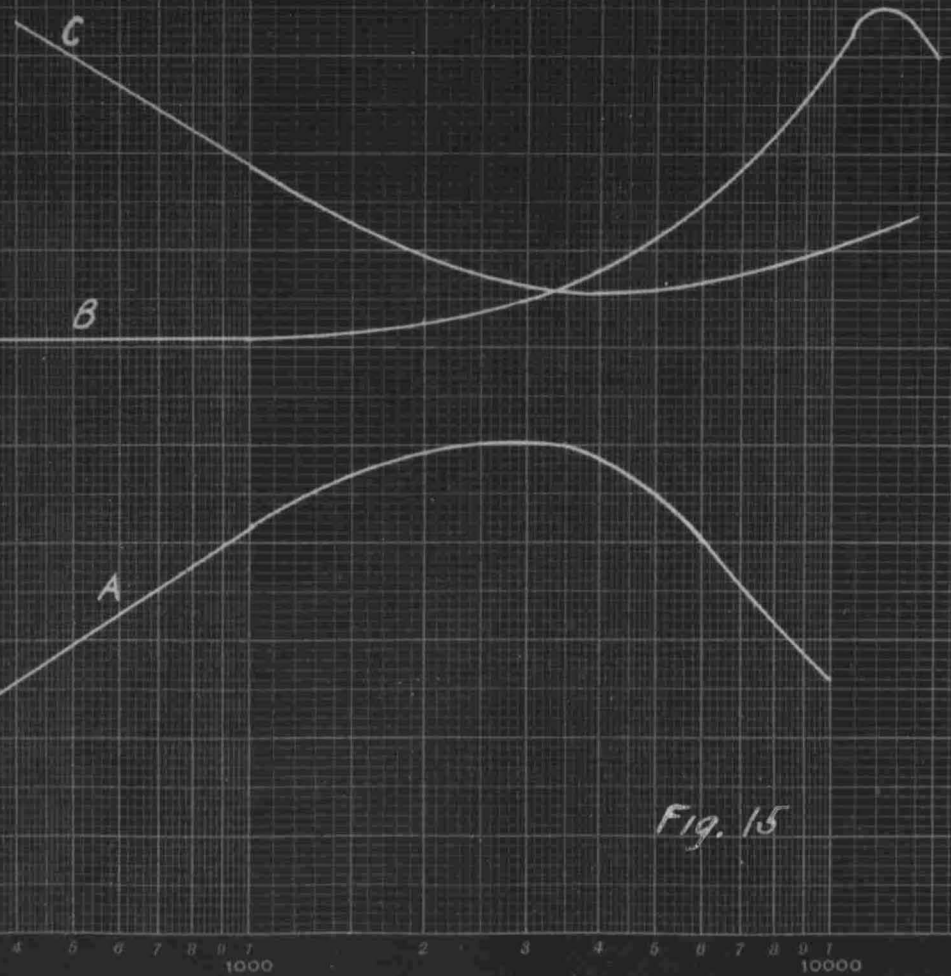
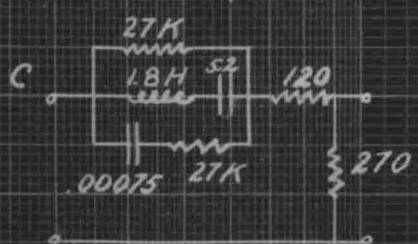
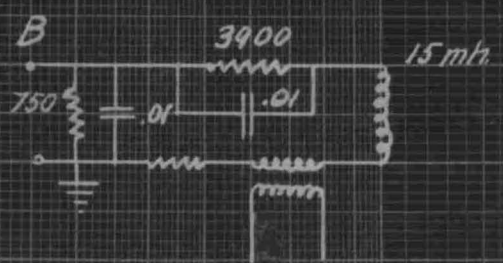


Fig. 15

FREQUENCY IN CYCLES PER SECOND

Composite Curves obtained by Adding Curves of Figure 15

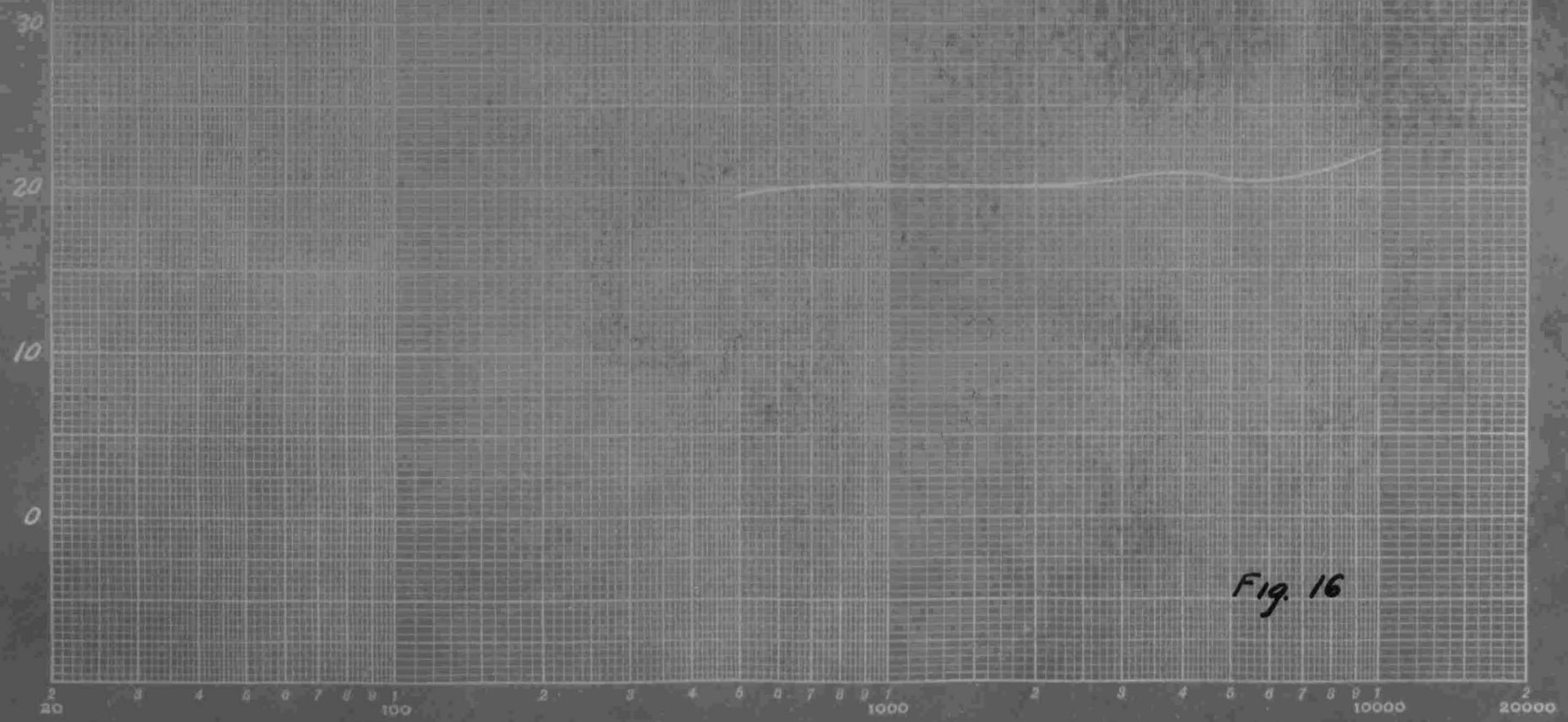


Fig. 16

FREQUENCY IN CYCLES PER SECOND

Actual Overall Frequency Response of System with
Components of Figure 15, Tape Speed 15" / second

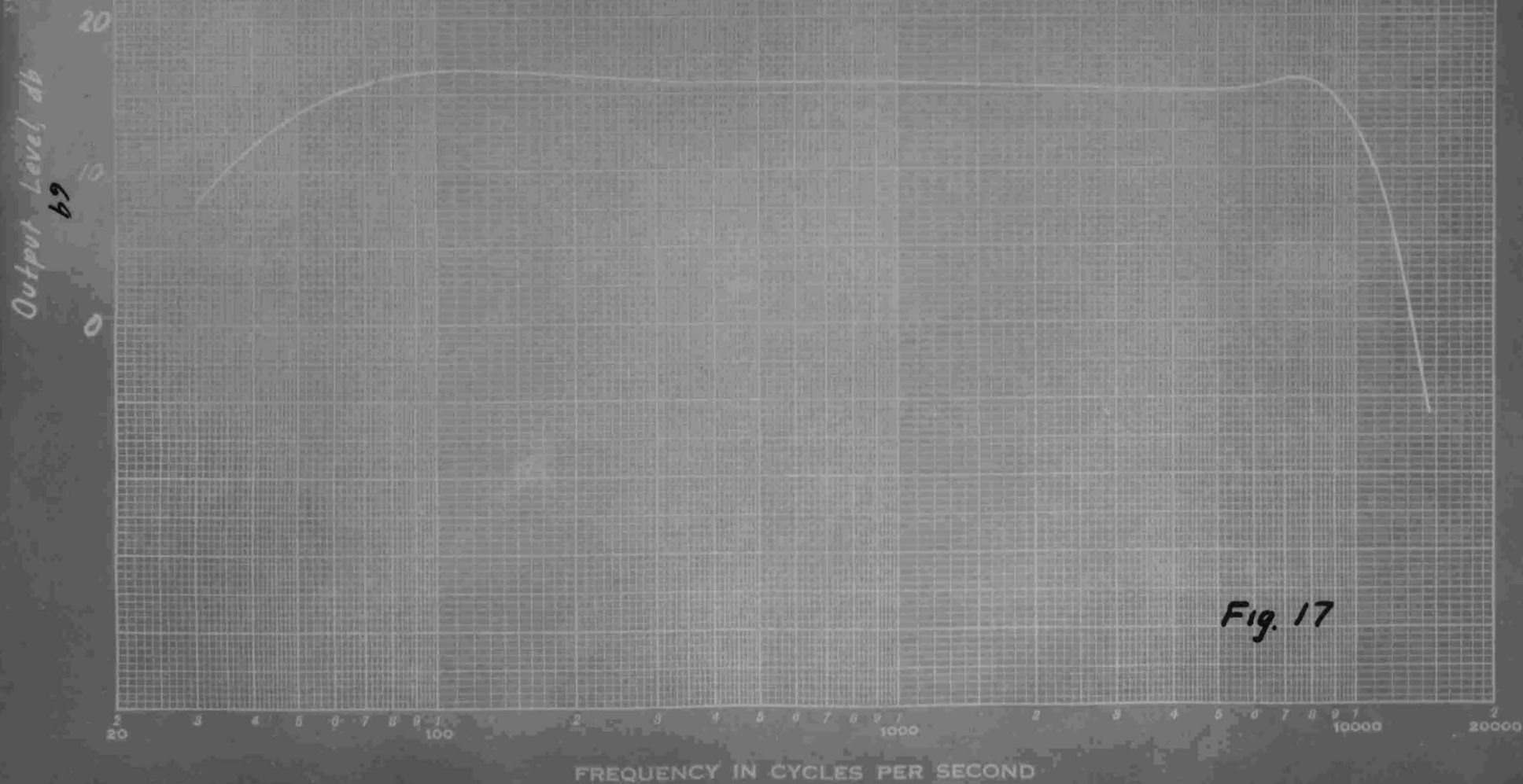
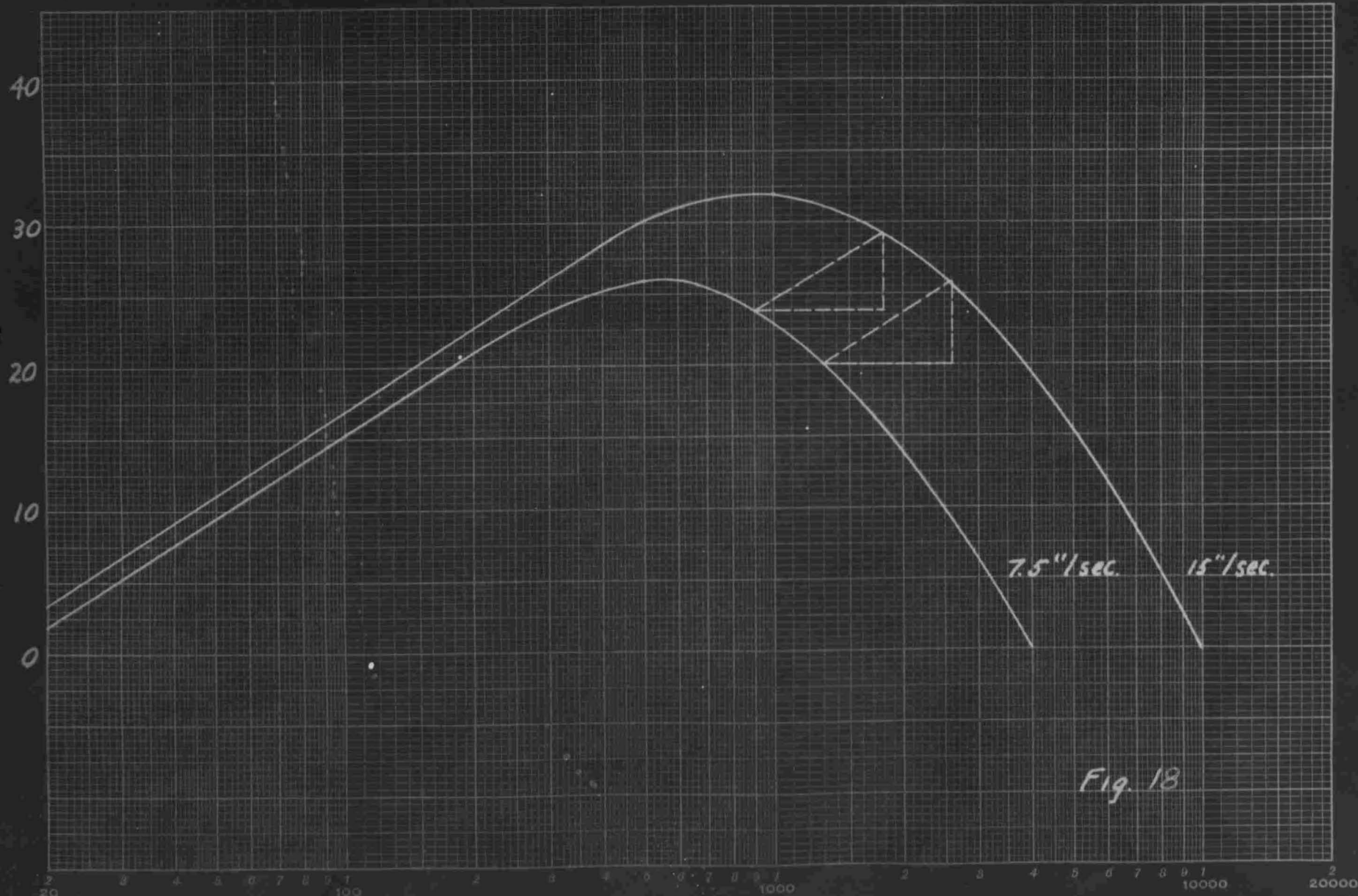


Fig. 17

Output in db



FREQUENCY IN CYCLES PER SECOND

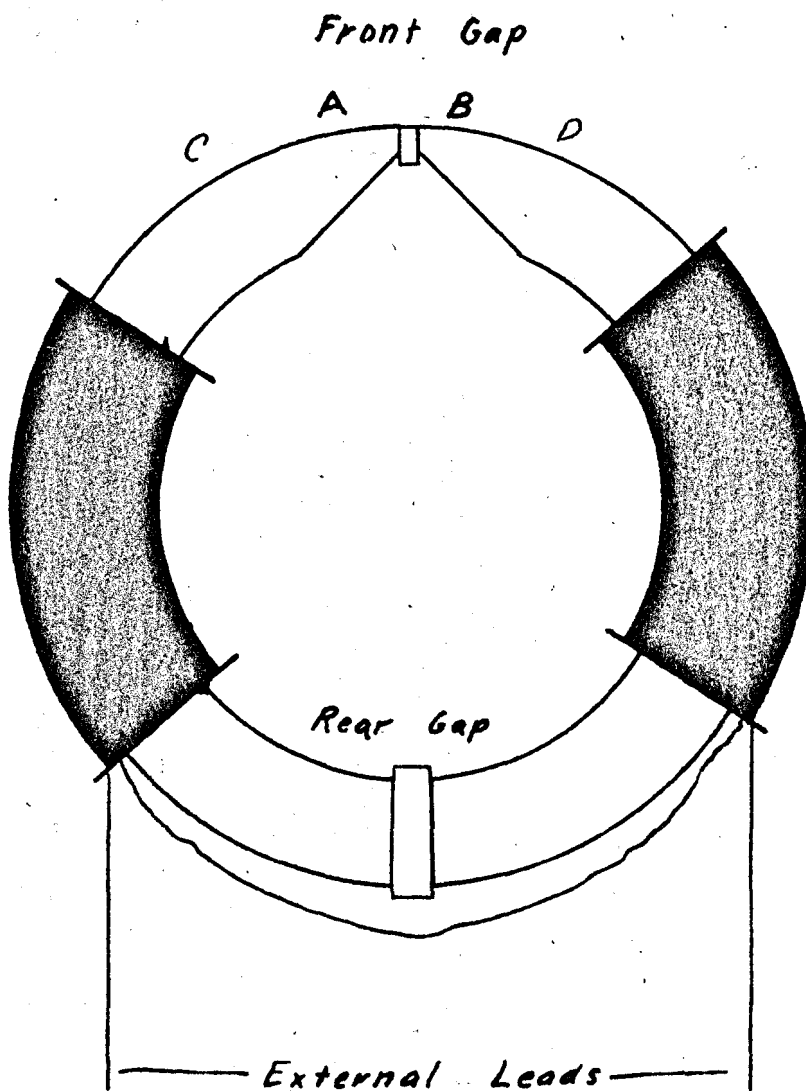


Fig. 19.

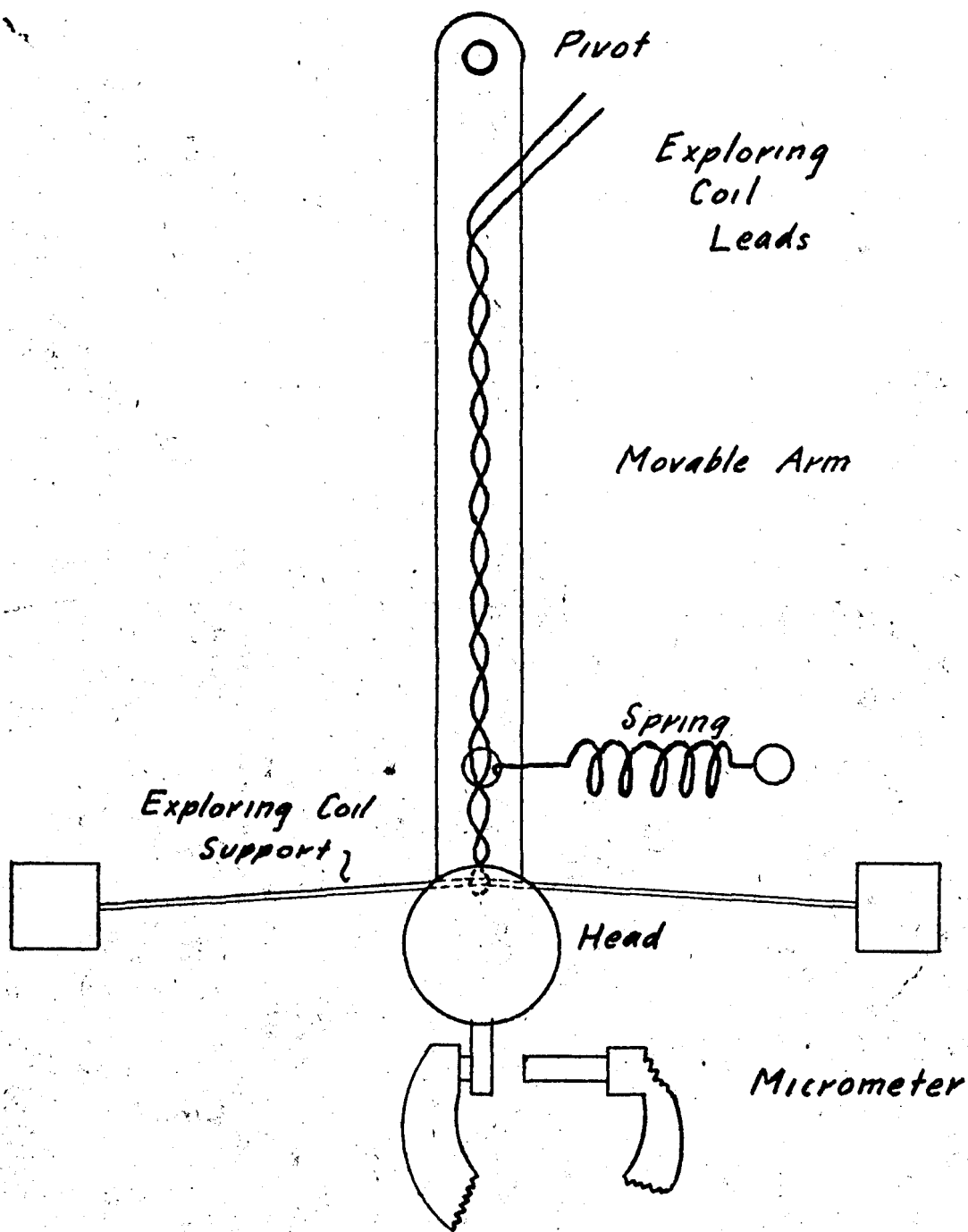


Fig. 20.

Reproducing Level in db

EL

Input-Output Curve with
Optimum H.F. Bias.

Frequency 700 CPS

Tape noise -44 db

System noise -80 db

German Type C Tape

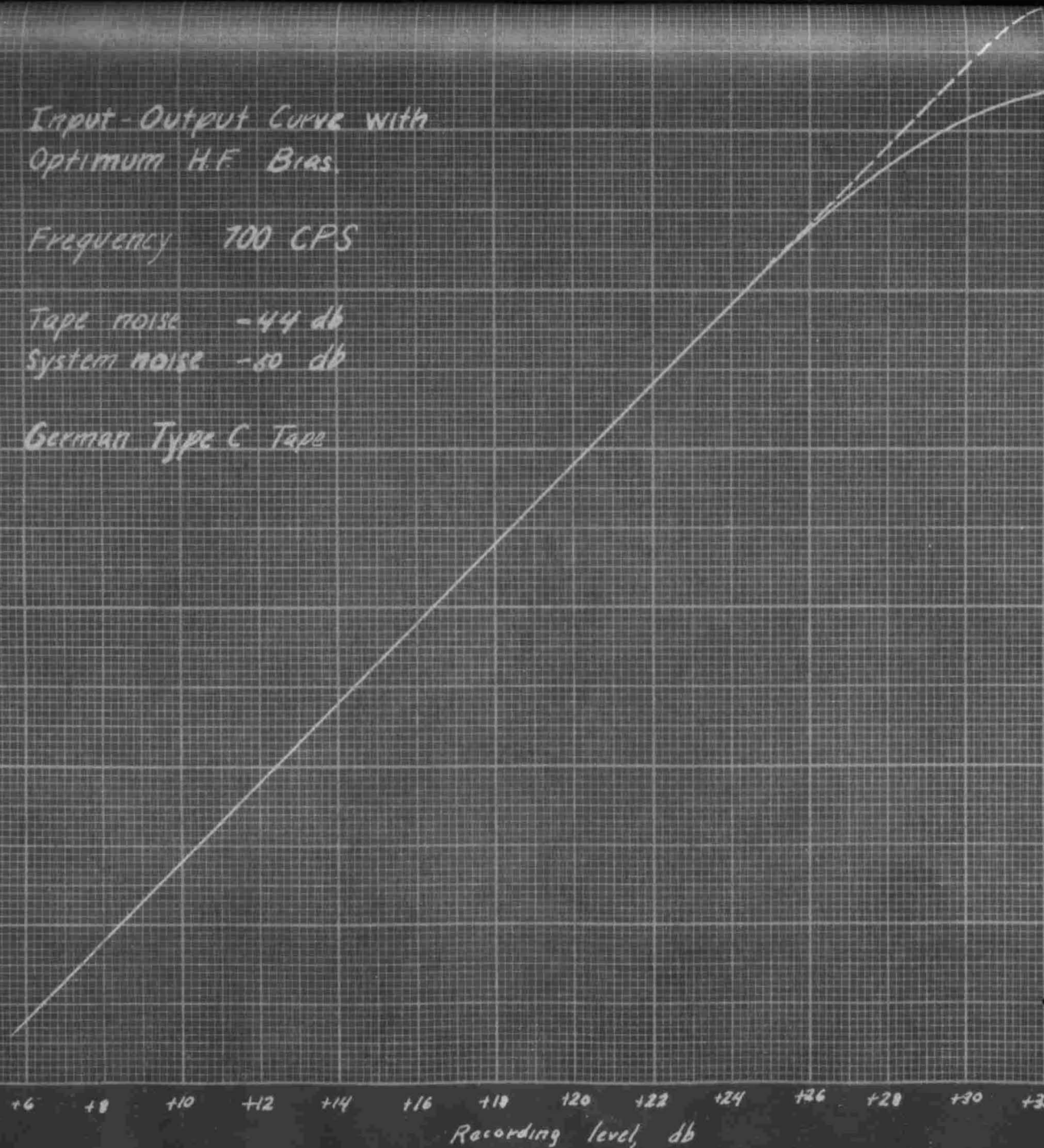


Fig. 21

Reproducing Level, db HL

+2
+4
+6
+8
+10
+12
+14
+16
+18
+20
+22
+24
+26
+28

Minnesota Minna (Plastic Base)
DuPont MT-78
DuPont MT-94
German Type C

Input-Output Curve with
Optimum H.F. Bias

Frequency 700 cps

System Noise -50 db

Tape Noise

German Type C -44 db
DuPont MT-94 -48 db
MT-78 -38 db
M.M. Plastic Base -40 db

Fig. 22

Recording Level, db

+2 +4 +6 +8 +10 +12 +14 +16 +18 +20 +22 +24 +26 +28 +30 +32 +34 +36 +38

Reproducing level, db, *92*

+28

+26

+24

+22

+20

+18

+16

+14

+12

+10

+8

+6

+4

+2

Input-Output Curve with
Optimum H.F. Bias

Frequency 700 cps

Tape Noise -44 db

System Noise -50 db

German Type LG Tape

+2 +4 +6 +8 +10 +12 +14 +16 +18 +20 +22 +24 +26 +28 +30 +32

Recording Level, db

Fig. 23

Reproducing Level, db 9L

+28
+26
+24
+22
+20
+18
+16
+14
+12
+10
+8
+6
+4
+2

Input-Output Curve with
Optimum H.F. Bias

Frequency 700 cps

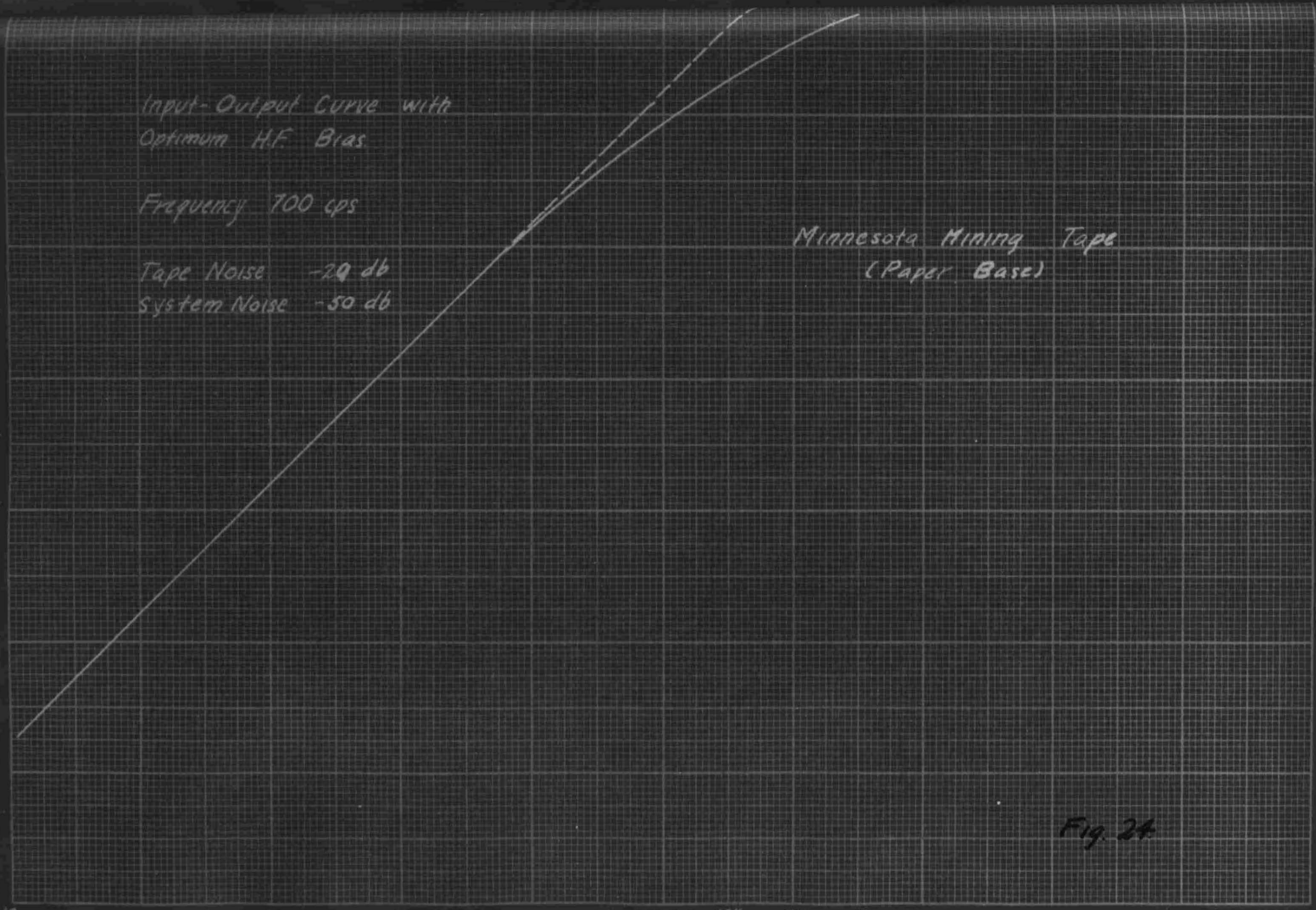
Tape Noise -29 db
System Noise -50 db

Minnesota Mining Tape
(Paper Base)

Recording Level, db

+2 +4 +6 +8 +10 +12 +14 +16 +18 +20 +22 +24 +26 +28

Fig. 24



Total Harmonic Distortion vs.
Reproducing Level

Frequency 400 cps

Optimum H.F. Bias

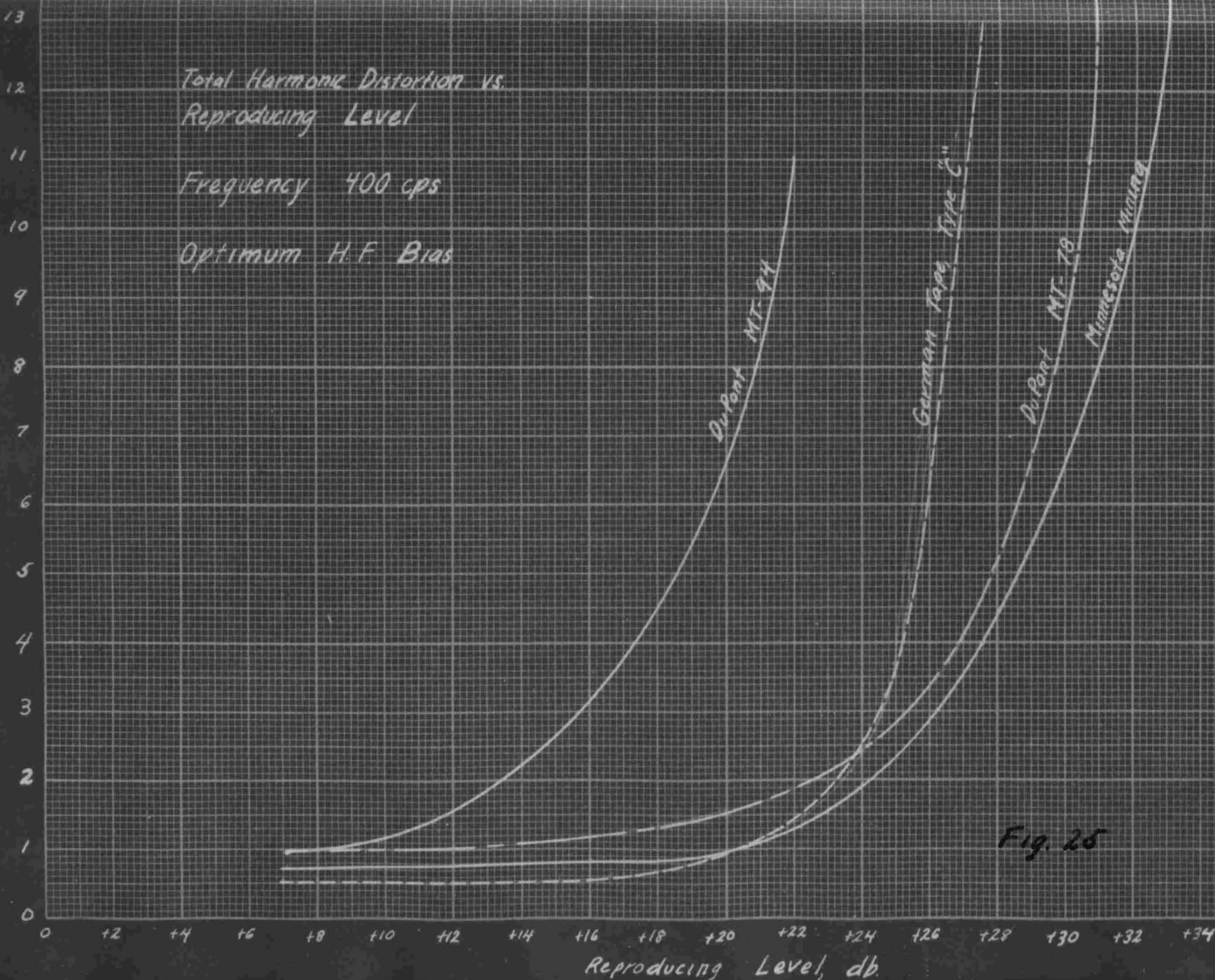


Fig. 25

Distortion vs. Reproducing Level for Five Values of H.F. Bias.

Frequency 400 cps

German Heads

German Type "C" Tape

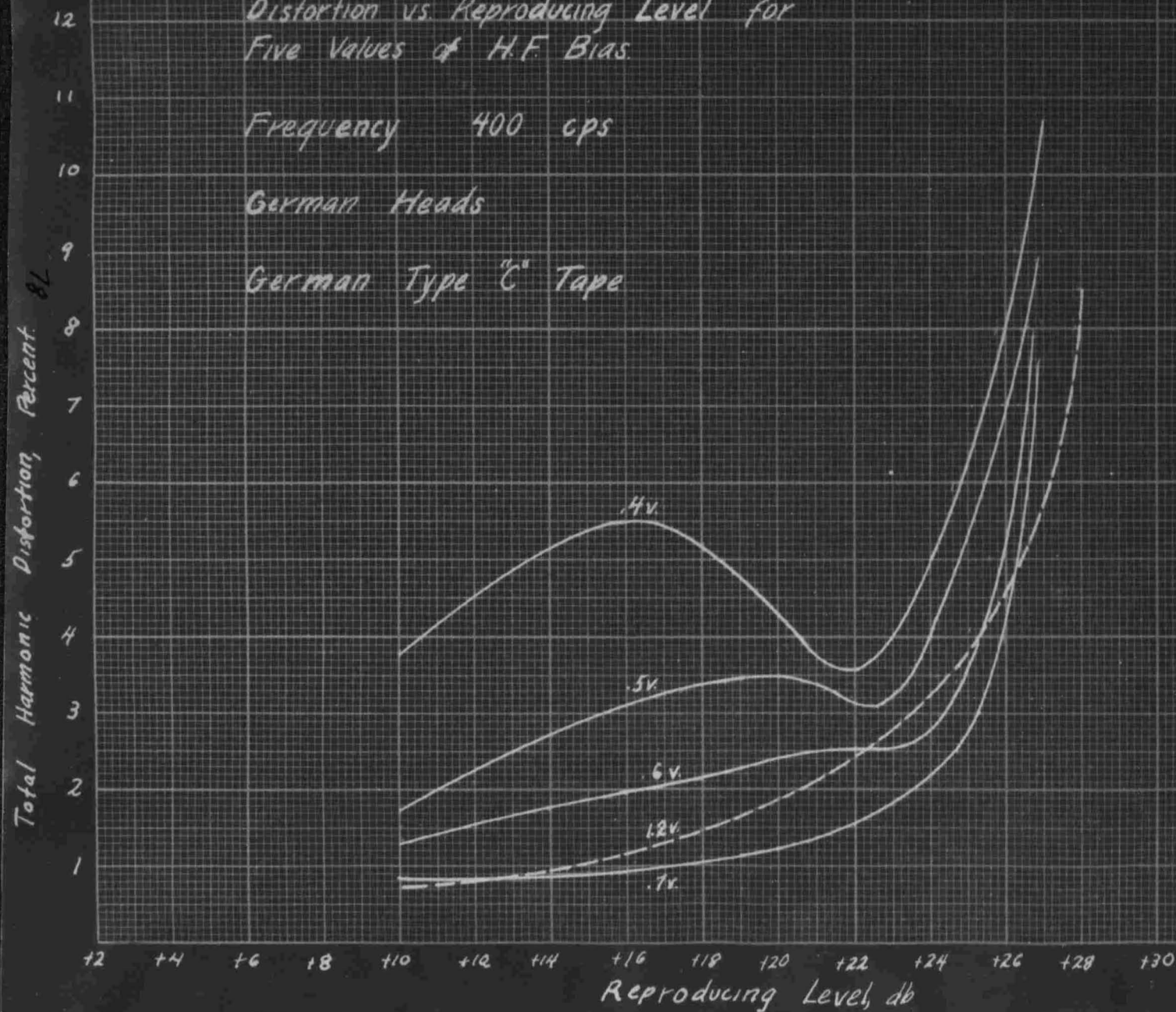


Fig. 25

67
Total Harmonic Distortion,
Percent

0
1
2
3
4
5
6

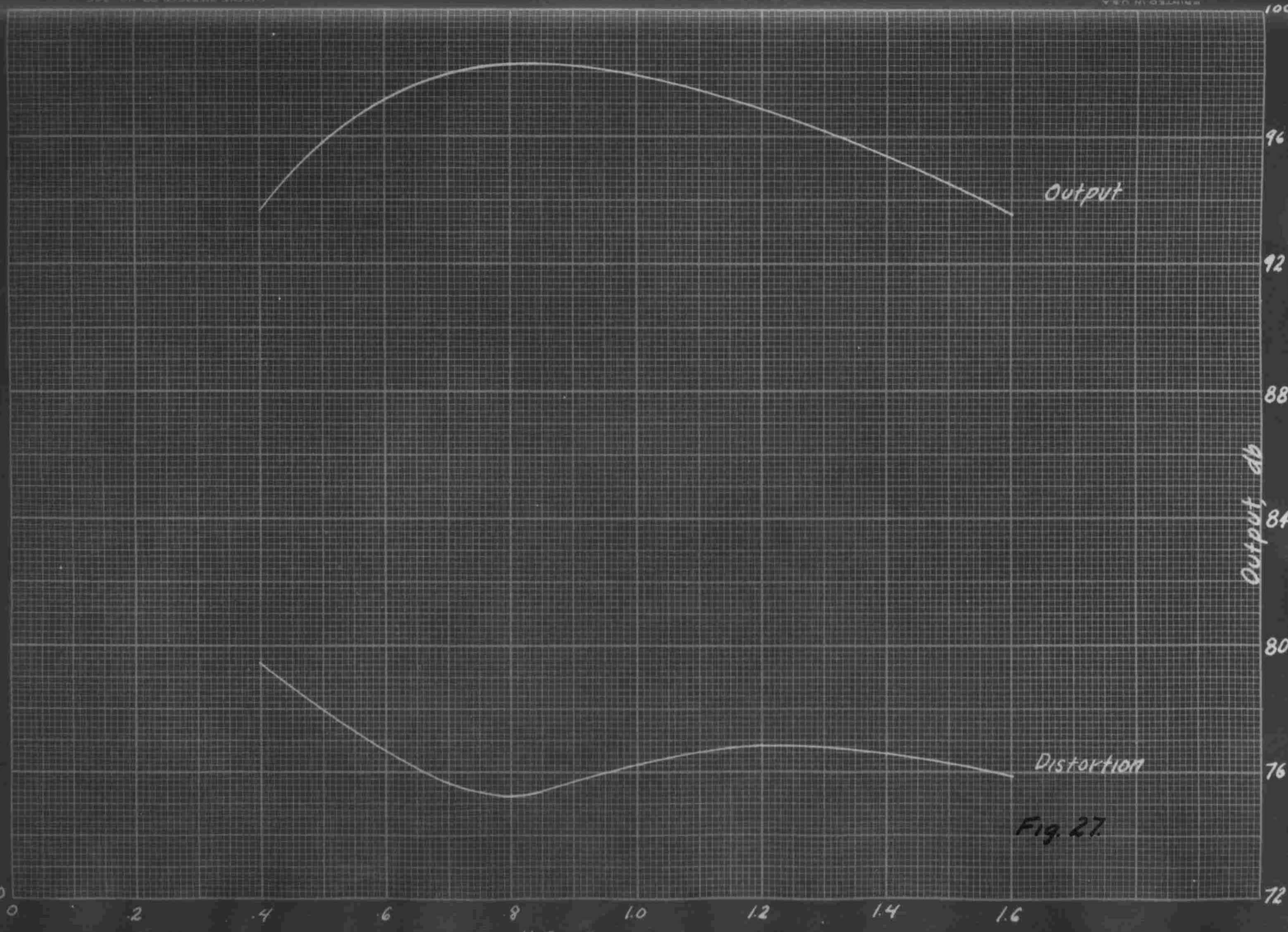


Fig. 27

Output, db

100
96
92
88
84
80
76
72

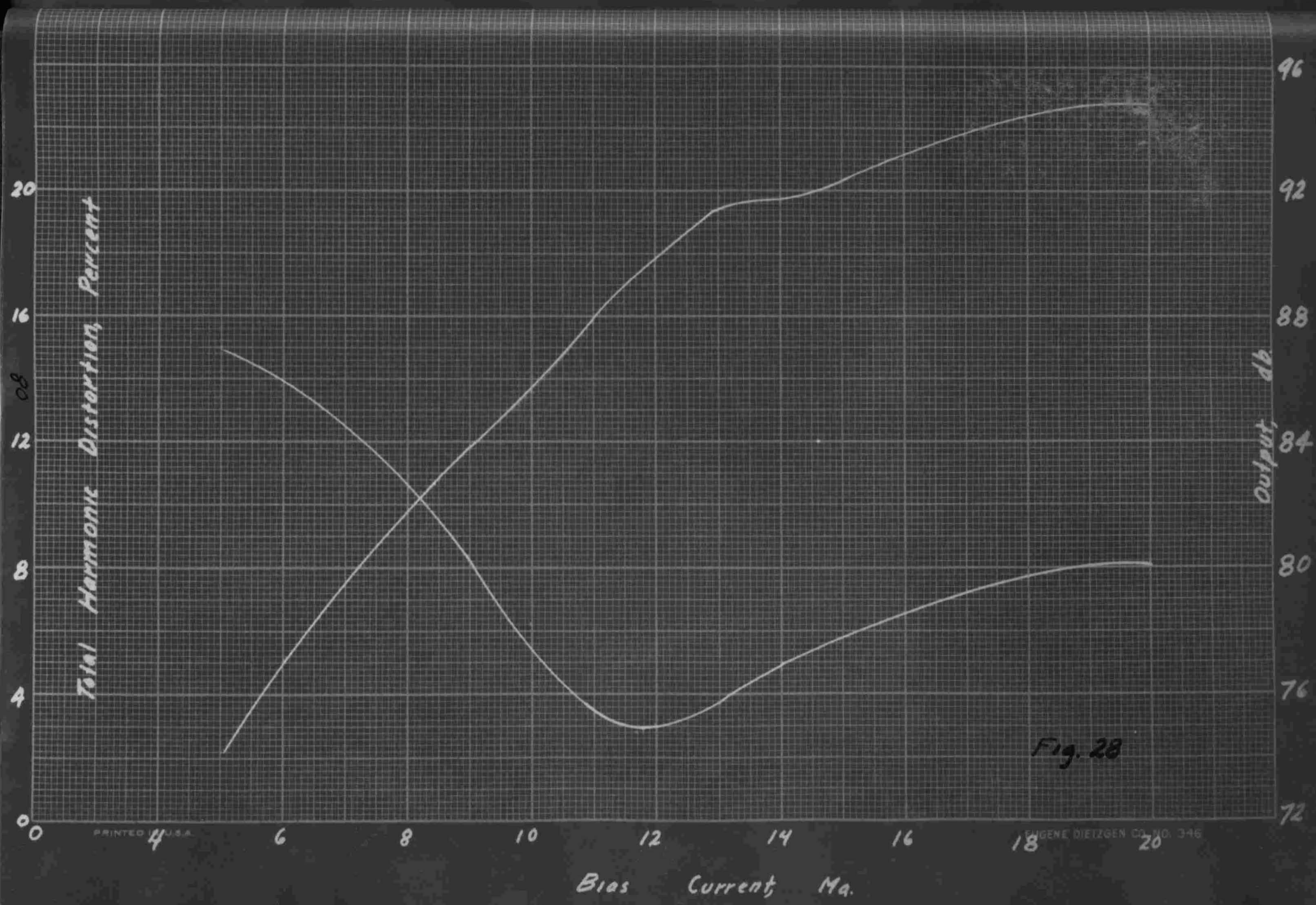


Fig. 28

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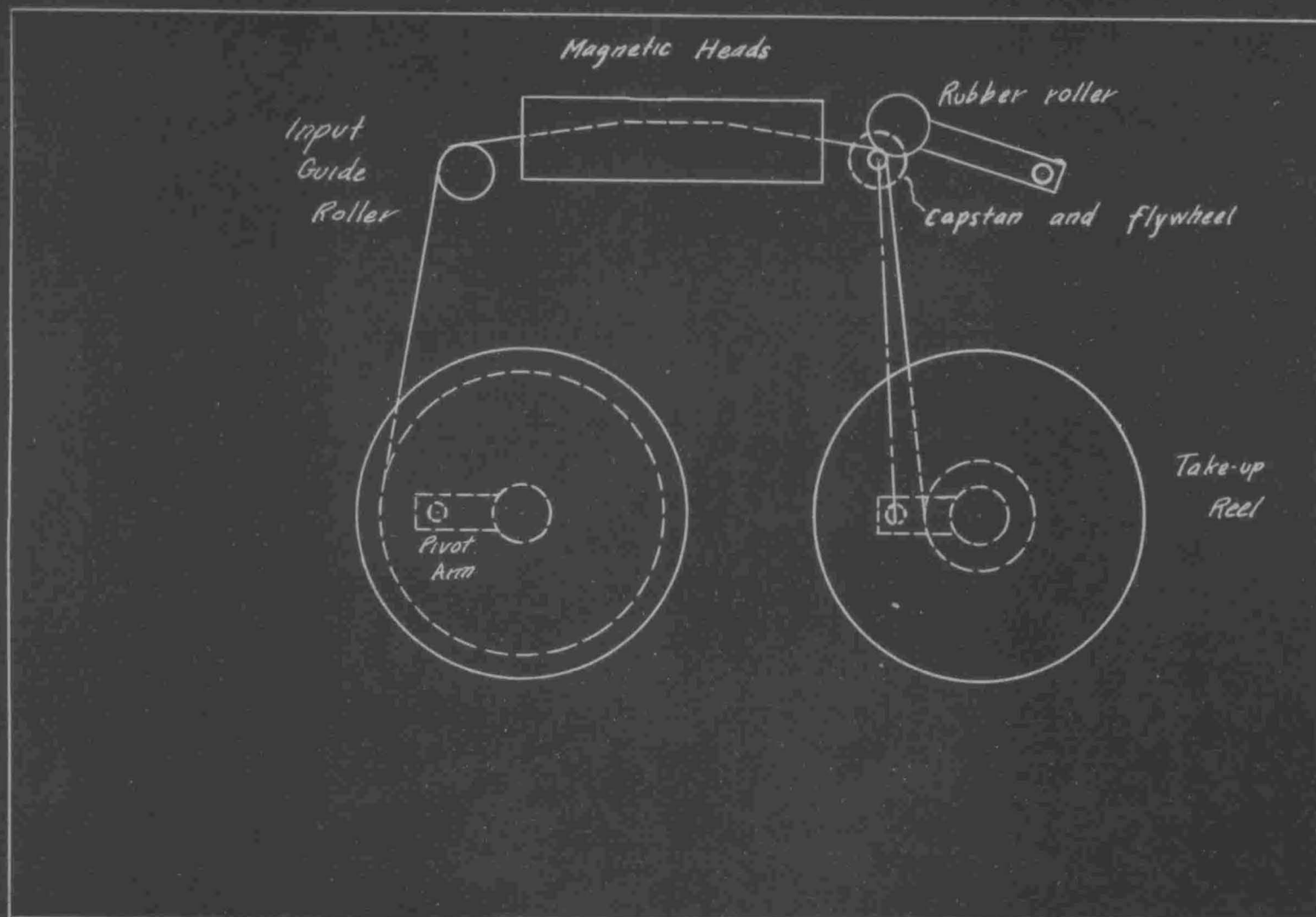


Fig. 29



Fig. 30